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MOLDING SPECIMENS FOR THE IMMERSION-COMPRESSION TEST

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

In This Issue

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A TEST FOR DETERMINING THE EFFECT OF WATER ON BITUMINOUS MIXTURES

BY THE DIVISION OF PHYSICAL RESEARCH, PUBLIC ROADS ADMINISTRATION

Reported by J. T. PAULS, Principal Highway Engineer, and H. M. REX, Materials Engineer

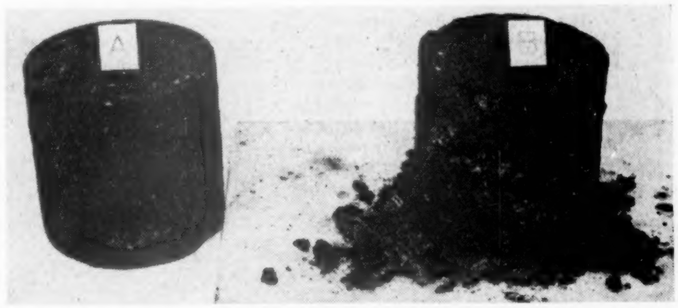
IT IS WELL KNOWN that bituminous mixtures containing aggregates of certain types and characteristics are susceptible to the action of water and, as a result, many tests and specifications have been developed to regulate, or to eliminate entirely, the use of the more water-sensitive materials.

One of the most familiar water-sensitive materials is clay. Specifications governing many types of bituminous road construction require that the aggregate shall be free from clay, or that the aggregate particles shall be free from adhering films of clay. Other requirements for control of this material limit the plasticity index and liquid limit for the aggregate fraction passing a No. 40 sieve. Volume change is one manifestation of the presence of clay in a bituminous mixture, and a swell test has been developed and widely used as a means of control.

A different type of water sensitivity has been found to be inherent in the aggregate itself. This characteristic has been described as the preferential affinity of aggregate particles for bitumen or water in the presence of both. An outward manifestation of this characteristic is the propensity of the aggregate particles to retain or lose a bituminous film when exposed to the action of water. An aggregate that tends to retain a large percentage of bituminous coating under such conditions has come to be classed as hydrophobic and one that tends to lose a bituminous film as hydrophilic.

In order to test the hydrophilic or hydrophobic properties of aggregates, several tests have been devised. A bibliography on the subject appears at the end of this report. The Nicholson test, the Oberbach test and modifications thereof, various scrubbing tests, etc., have been widely used by investigators. Whatever the advantage peculiar to each of these stripping tests, there are several serious disadvantages common to all. First, only one size fraction of the whole aggregate is usually selected for test. Second, estimation of the extent of stripping is made by visual observation—a method seriously lacking in precision. Third, results of such tests give no indication of the actual degree of adhesion of the bituminous film to the aggregate particle. When the less viscous bituminous materials are used with certain aggregates, it has been observed that water will loosen or separate the film from the aggregate particle without, however, disturbing the continuity of the film. Failure of this type is not reflected in the results of the usual stripping test. Fourth, and most significant, there is no direct relation between the results obtained by any of the stripping tests and the effects that will be obtained when the complete bituminous mixture containing the aggregate in question is exposed to the action of water.

It is believed that there is a distinct need for a test that will measure positively the effect of the presence of water-sensitive materials of any type in bituminous mixtures when such mixtures are exposed to the action of water. This report relates the development and describes the procedure of a test capable of performing this function, and presents data to demonstrate its usefulness.



EFFECT OF IMMERSING MOLDED SPECIMENS IN WATER. SPECIMEN A CONTAINS HYDROPHOBIC AGGREGATE AND SPECIMEN B CONTAINS HYDROPHILIC AGGREGATE. SPECIMEN B HAS LOST ALL STABILITY.

DISAPPOINTING RESULTS OF COLORADO EXPERIMENTAL SECTIONS LEAD TO LABORATORY STUDY

In the spring of 1942, a laboratory study was made of aggregates and bituminous materials that had been used in experimental road surfacing by the Colorado State Highway Department, in cooperation with the Public Roads Administration. It was intended to study the usefulness of a requirement for viscosity index in specifications for slow-curing (SC) liquid asphaltic materials by constructing and observing a number of test sections in which the only variable would be the viscosity index of the bituminous materials.

The experimental sections were constructed in the fall of 1941, and the work consisted of reconditioning and priming the base and mixing and laying a 1½-inch bituminous mat composed of SC–3 (slow-curing) material and local aggregates. Thirteen different asphaltic materials of SC–3 grade were used in the experiment, each section of which was 3,700 feet in length.

The aggregate used in the bituminous mixture was obtained from a local pit adjoining the highway. The pit material was fairly uniform in quality and grading and, judged by existing standards and specifications, gave no indication that unsatisfactory behavior would result from its use.

A typical grading is given below. Other physical characteristics of the aggregate used in the construction are shown in table 1.

TABLE 1.—*Physical properties of aggregate*

Aggregate	Specific gravity		Absorption	Voids by vibration
	Bulk	Apparent		
			Percent	*Percent*
17 percent retained on No. 4 sieve	2.50	2.62	1.76	
83 percent passing No. 4 sieve	2.44	2.60	2.48	
100 percent total aggregate		2.60		28.4

Sieve size:	Total percent passing
¾-inch	100
⅜-inch	90
No. 10	70
No. 40	36
No. 200	15

The governing specifications for the bituminous material were as follows:

Water and sediment, percent	2−
Flash point, °F	200+
Furol viscosity, 140° F., seconds	150–300
Distillation test, total distillate off at—	
600° F., percent by volume	10−
680° F., percent by volume	20−
Tests on the distillation residue:	
Float test, 122° F., seconds	25+
Solubility in CCl_4, percent	99.5+
Oliensis test	Negative
Viscosity index	Variable [1]
Residue of 80 penetration, percent	65–75
Ductility tests on residue of 80 penetration:	
77° F., 5 cm. per min., cm	100+
39.2° F., ¼ cm. per min., cm	5+

Behavior of the test sections, however, was disappointing. Rapid deterioration of the surfacing began with the first rains. The surface softened to a slight depth after each rain and became slimy under traffic. Upon drying, the surface raveled, leaving the larger aggregate particles exposed. This action continued, with the result that by early spring in 1942 a considerable thickness of surface had been lost. Consequently, the objective sought in these experiments, namely, to determine whether or not the viscosity index is a significant test requirement, was not attained. Any differences attributable to variations in bituminous materials that might otherwise have been apparent were completely obscured by the predominant effect of the particular aggregate used.

LABORATORY STUDY SUGGESTS NEED FOR A MORE INFORMATIVE TEST

Samples of the aggregate and of the road mixtures had been sent to the laboratory at the time the road sections were built. The laboratory testing schedules for the aggregate included determinations of absorption, specific gravity, vibratory density, and stripping by the modified Nicholson test procedure.

In the Nicholson test, 95 grams of the aggregate passing a ⅜-inch sieve and retained on a No. 4 sieve is combined with 5 grams of bituminous material and mixed by hand until a uniform coating of the aggregate is obtained. This sample is then placed in an oven maintained at a constant temperature of 140° F. for 24 hours. After removing from the oven, the sample is allowed to cool to room temperature, after which approximately 50 grams is placed in an Erlenmeyer flask of 250 milliliters capacity, and covered with 175 milliliters of distilled water. The flask is then stoppered and placed in the rotating frame of the agitating machine. The speed of rotation is 43 rotations per minute. The water bath in the machine is maintained at 77° F. for the first 30 minutes of the test. At the expiration of 1, 3, 5, 10, 15, and 30 minutes from the time of starting the test, the machine is stopped and the area of aggregate coated with bitumen is estimated. The temperature of the water in the machine is then raised to 100° F., and agitation resumed for an additional 15 minutes, after which the machine is stopped and the extent of uncoating estimated as before. A final 15 minutes of agitation with the water bath at a temperature of 120° F. ends the test. It is believed that the last 15 minutes of agitation with the water at 120° F. is too severe to be significant except when hot mixtures are being tested. Therefore, only the results at 77° and 100° F. for time intervals up to 45 minutes are included in this report.

[1] Materials were selected to cover a wide range of viscosity index.

Stripping tests, by this method, were made on four samples prepared in the laboratory. The bituminous materials used were: (1) An SC–3 slow-curing material actually used in one of the test sections, and (2) an MC–3 cut-back material, characteristics of which are shown in table 7. The latter material was included so as to compare the results with a cut-back material. The aggregates were that used on the Colorado job and Potomac River gravel. The Potomac River gravel was tested in combination with the two grades of bituminous material for the purpose of comparison.

Results of these tests are given in table 2.

TABLE 2.—*Results of modified Nicholson tests on Colorado and Potomac River aggregates*

Source of aggregate	Type of bituminous material	Estimated area coated: Water at 77° F. (30 min.)	Estimated area coated: Water at 100° F. (45 min.)
		Percent	*Percent*
Potomac River gravel	SC-3	95	95
	MC-3	100	100
Colorado aggregate	SC-3	50	40
	MC-3	50	40

TABLE 3.—*Degradation of the Colorado aggregate by the action of water*

Sieve size	Weight: Original	Weight: After 24 hours in water	Loss	Loss
	Grams	*Grams*	*Grams*	*Percent*
¾-inch–⅜-inch	78.0	73.1	4.9	6.7
⅜-inch–No. 4	100.0	87.2	12.8	12.8
No. 4–No. 8	100.0	89.8	10.2	10.2
No. 8–No. 16	100.0	89.9	10.1	10.1
No. 16–No. 30	100.0	87.7	12.3	12.3
No. 30–No. 50	100.0	85.9	14.1	14.1

TABLE 4.—*Results of laboratory tests on 3- by 3-inch cylinders molded from field mixtures*

Field mix section No.	Vertical swell after immersion in water, unconfined		Compressive strength				
			Strength of dry specimens	After immersion in water			
				1 day		7 days	
	1 day	7 days		Strength	Strength retained	Strength	Strength retained
	Percent	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Lb. per sq. in.*	*Percent*
1	1.4	4.9	43	19	44	5	12
2	2.4	4.0	46	7	15	4	9
3	2.5	3.8	59	6	10	4	7
4	1.5	2.9	52	17	33	5	10
5	.7	2.6	55	24	44	7	13
6	.8	2.2	38	21	55	7	18
7	1.2	2.9	54	17	31	4	7
8	1.0	2.5	38	17	45	7	18
9	.6	2.5	53	26	49	6	11
10	1.0	2.9	61	24	39	6	10
11	.7	2.7	64	33	52	10	16
12	.5	2.7	71	32	45	9	13
13	.7	2.5	69	33	48	8	12

TABLE 5.—*Results of immersion and compression tests on 3- by 3-inch cylinders composed of laboratory mixtures containing Colorado and Potomac River aggregates*

Aggregate	Bitumen		Vertical swell of unconfined specimens after immersion in water		Compressive strength			Retained strength after immersion	
	Grade and type	Proportion by weight of aggregate	1 day	7 days	As molded	After immersion in water at 77° F. 1 day	After immersion in water at 77° F. 7 days	1 day	7 days
		Percent	*Percent*	*Percent*	*Lb. per sq. in*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Percent*
Colorado pit run	SC–3 [1]	5.5	5.0	5.4	41	1	[2]	2	0
Colorado pit run	MC–3	6.0	3.5	4.4	79	4	3	5	4
Potomac River sand-gravel with limestone dust.[3]	SC–3 [1]	5.5	.5	.6	15	15	13	100	87
Potomac River sand-gravel with limestone dust.[3]	MC–3	6.0	.2	.2	31	32	30	103	97

[1] SC–3 material used in the field construction and in the stripping tests reported in table 2, p. 116.
[2] Disintegrated. [3] Size and grading made identical to that of the Colorado aggregate.

The Colorado aggregate showed substantially greater stripping tendencies than did the Potomac River gravel. It is also of interest to note that substitution of MC–3 for SC–3 material gave essentially identical results with both aggregates. However, the results of this single test on one fraction of the Colorado aggregate did not afford sufficient evidence to warrant a prediction of failure of the type that occurred on the test sections. It seemed evident that characteristics of the aggregate other than stripping had an important effect on the behavior of the bituminous mixture in its resistance to the action of moisture.

Early in the laboratory investigation it became apparent that degradation of the Colorado aggregate followed exposure to water. In order to establish some quantitative measure of this effect, the following soundness test was made.

Portions of six different size fractions were selected for test. After sieving to refusal, the several fractions, each resting on the respective sieve on which it was retained, were placed in pans of suitable depth. Distilled water was added to each pan to an elevation of about one-half inch above the aggregate. The pans and contents were covered. After 24 hours the sieves were removed from the water and the retained material dried, again sieved to refusal, and weighed. Results of this test are shown in table 3. The differences in weight shown represent the losses of the original fractions due to the action of water.

Such a break-down can occur only in a structurally weak aggregate. It is also reasonable to suppose that this tendency to degrade affected the results of the Nicholson test. No doubt considerable area reported as stripped represented newly exposed faces produced by splitting of the aggregate particles in water as the test proceeded.

Although results of the Nicholson test and the soundness test showed that the Colorado aggregate was strongly susceptible to water action, there was still lacking conclusive evidence by any laboratory test of how a bituminous mixture containing this aggregate would perform when exposed to the action of water. It was at this point that the idea was conceived of comparing the compressive strength of dry molded specimens of the mixtures with the strength of specimens that had been immersed in water.

Samples of the oil-aggregate mixture of each of the 13 sections, upon completion of the mixing operations in the field, had been sent to the laboratory. Using these mixtures, cylindrical specimens, 3 inches in diameter and 3 inches in height, were molded at room temperature using a molding pressure of 1,000 pounds per square inch, and maintaining the load for 1 minute.

Specimens from each mix were tested in compression immediately after molding, and after immersion in water for periods of 1 and 7 days. The volume change, or swell, of the immersed specimens, as indicated by the change in the vertical dimension, was also noted. The results of these tests are given in table 4.

In addition, mixtures composed of the Colorado aggregate as received and an SC–3 material were prepared in the laboratory. Mixtures containing Colorado aggregate and MC–3 material were also prepared. For the purpose of comparison similar mixtures were made in which each of the two bituminous materials was combined with Potomac River sand and gravel after it had been sieved and recombined to conform to the grading of the Colorado aggregate. Limestone dust was added to the Potomac River sand and gravel to bring the percentage of filler up to that naturally contained in the Colorado aggregate.

These laboratory mixtures were prepared by hand with the aggregates at air temperature and the bituminous materials heated to 175° F. Mixing was continued as long as improvement in coating could be observed. Prior to molding, the mixtures were placed in open pans in an oven, maintained at a temperature of 140° F. and cured for 24 hours. Cylindrical specimens 3 inches in diameter and 3 inches in height were molded, from these mixtures, using a molding pressure of 3,000 pounds per square inch, maintained for 1 minute.

The test procedure for the laboratory-prepared mixtures was the same as that described for the field mixtures. One set of specimens was tested immediately after molding, one set after 1 day immersion in water, and one set after 7 days of water immersion.

Typical results of immersion and compression tests of the mixtures prepared in the laboratory are shown in table 5.

USEFULNESS OF THE IMMERSION-COMPRESSION TEST INDICATED

Results of immersion-compression tests on specimens of field and laboratory mixtures containing the Colorado aggregate show striking loss of stability after immersion in water. The higher stability retained by specimens molded from the field samples, compared to that of specimens made from mixtures prepared in the laboratory was undoubtedly due to the more extensive curing to which the field mixtures had been subjected in the process of road mixing and in the interval between mixing and testing. In the laboratory mixtures con-

taining Colorado aggregate, substitution of MC–3 material for SC–3 material resulted in very little improvement in retention of stability. Comparable mixtures consisting of Potomac River sand-gravel and limestone dust, with either grade of bituminous material, lost little strength even after 7 days immersion, and in these mixtures considerable improvement resulted from the substitution of MC–3 for SC–3 material.

In general the vertical swell of the unconfined specimens varied consistently with the loss of stability. It is believed however that the increase in vertical dimension is not always a trustworthy index of volume change, and in later work the swell was calculated by comparing the volume of each specimen, as determined by displacement in water, before and after immersion.

In weighing the relative importance of the information obtained by the various tests in the Colorado investigation, it is believed that the data obtained by the immersion-compression test are the most significant in that, (1) the test utilized the whole aggregate instead of one fraction, (2) soundness of the aggregate is determined directly in terms of retention of stability of the entire mixture, (3) results are expressed in numerical values, unaffected by the personal factor involved in the estimation systems as used in the various stripping tests, and (4) the results are consistent with the service behavior of the materials in the road surface.

TESTS OF BITUMINOUS MIXTURES SHOW EFFECT OF VARYING TYPE AND QUANTITY OF FILLER

This method of test was considered so promising that it was used the following year in a laboratory study of the form and type of fillers commonly used in bituminous mixtures. Pulverized New York Avenue clay [2] was incorporated with Potomac River sand and gravel, both as a filler and as a coating on the surface of the particles of fine and coarse aggregate. In addition, mixtures were prepared in which limestone dust was used as the filler.

Two aggregate gradings were used in this work, ¾-inch-0 and ⅜-inch-0, as shown in table 6.

TABLE 6.—*Grading of aggregates used in the study of fillers*

Sieve size	Total amount passing— ¾-inch maximum size	Total amount passing— ⅜-inch maximum size	Sieve size	Total amount passing— ¾-inch maximum size	Total amount passing— ⅜-inch maximum size
	Percent	*Percent*		*Percent*	*Percent*
¾-inch	100		No. 14	39	68
½-inch	86		No. 30	31	45
⅜-inch	78	100	No. 50	19	23
No. 4	60	94	No. 100	12	16
No. 8	48	83	No. 200	9	10

In preparing the clay-coated aggregate, the clean aggregate was first moistened with water, then the pulverized clay was added and stirred until all particles seemed to be uniformly covered with a clay coating. The coated aggregate was then dried to a moisture-free condition, accompanied by constant stirring to minimize agglomeration. Bituminous material was then added. In the mixtures containing clay and limestone dust as fillers, the dry powders were mixed thoroughly with the dry aggregate before adding bituminous material.

[2] A plastic clay soil found in the vicinity of Washington, D. C., and designated as tuxedo clay by the Bureau of Plant Industry, U. S. Department of Agriculture.

TABLE 7.—*Characteristics of bituminous materials used*

Characteristics	Type and grade of cut-back material: RC–4	MC–2	MC–3	Asphalt cement, 85–100 penetration
Specific gravity 77°/77° F	0.985	0.966	0.978	1.018
Flash point, ° F	120	135	160	304
Furol viscosity, at 140° F		145.9	358	
Furol viscosity, at 180° F	183			
Distillation:				
Distillate, percent by volume to 680° F	14.5	24.5	22.0	
Tests on distillation residue:				
Penetration, 77° F., 100 gm., 5 sec.	97	194	191	85
Ductility, 77° F., 5 centimeters per minute, centimeters	208	122	127	110+
Total soluble in CCl_4, percent	99.91	99.92	99.88	
Total soluble in CS_2, percent				99.90
Oliensis spot test	Negative	Negative	Negative	

Three grades of bituminous material were used in this study, namely, 85–100 penetration asphalt cement, MC–3 cut-back and RC–4 cut-back asphalt, the more important characteristics of which are shown in table 7. The bitumen content of all mixtures was 6 parts bitumen to 100 parts of aggregate by weight.

Sufficient aggregate and bitumen for each test specimen were mixed by hand in individual batches. Mixing time was dictated by the ease or difficulty of coating the aggregate. In the case of the clay-coated aggregates some care in mixing was necessary, in order to avoid scuffing of the clay coating.

Mixing was done over a hot plate, and the following temperatures for batches representing the three types of bituminous material were not exceeded during the mixing process: Asphalt cement mixtures, 260° F.; MC–3, 120° F.; and RC–4, 160° F.

Test specimens of the asphalt-cement mixtures were molded immediately after mixing. Mixtures containing cut-back materials however were cured loose for 20 hours before molding—the batches with MC material in an oven at 140° F., and the batches with RC material at laboratory temperature. Mixtures with cut-back material were molded at air temperature.

Test specimens were cylinders, 4 inches in diameter and 4 inches in height, molded between double plungers under a load of 3,000 pounds per square inch. The molded specimens representing each combination of aggregate and bituminous material were cured in an oven at 140° F. for periods of 1 and 7 days. Some of the specimens representing each curing condition were tested in compression without water immersion while others were tested after immersion in water for 7 days. After removal from the water and just before testing, the swell of each specimen was noted. The platen speed of the testing machine was 0.2 inch per minute. An abstract of the test results is shown in table 8.

In general, the effect of immersion in water on the stability of the specimens was influenced by three factors, namely, the type of filler (plastic or nonplastic), the distribution of filler material (throughout the mixture or concentrated as a coating on the aggregate particles), and the characteristics of the bituminous material.

In all cases those specimens containing more than a slight amount of clay lost strength by a larger percentage than did those containing nonplastic filler. For the mixtures containing limestone-clay filler blends, the percentage loss was directly proportional to the percentage of clay contained. Specimens containing clay-coated aggregate showed the lowest percentage of re-

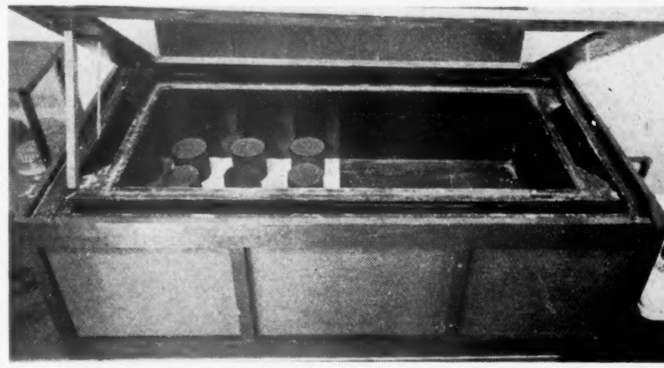
TABLE 8.—*Effect of immersion on stability of 4- by 4-inch specimens containing Potomac River sand and gravel in combination with plastic and nonplastic fillers.*

Quantity and type of filler	Air voids	Curing at 140° F.	Immersion	Swell	Compressive strength	Strength retained
85-100 PENETRATION ASPHALT ¾-INCH MAXIMUM SIZE AGGREGATE						
	Percent	*Days*	*Days*	*Percent*	*Lb. per sq. in.*	*Percent*
9-percent limestone dust as filler	3.7	7	0		366	
	3.7	7	7	0	351	96
9-percent clay as filler	4.9	1	0		408	
		1	7	2.1	336	83
		7	0		460	
	4.9	7	7	1.4	369	80
8-percent clay as film on particles, 1-percent clay as filler	7.0	1	0		393	
	6.1	1	7	4.0	187	48
	7.0	7	0		418	
	6.6	7	7	3.2	243	58
RC-4 CUT-BACK MATERIAL ¾-INCH MAXIMUM SIZE AGGREGATE						
9-percent limestone dust as filler	3.3	1	0		152	
	4.1	1	7	0.5	166	109
	4.1	7	0		287	
	3.8	7	7	.6	257	90
9-percent clay as filler	3.8	1	0		247	
	4.1	1	7	2.6	146	59
	3.8	7	0		435	
		7	7	1.7	266	61
8-percent clay as film on particles, 1-percent clay as filler		1	0		232	
	4.6	1	7	6.3	66	28
		7	0		361	
	4.6	7	7	4.4	134	37
RC-4 CUT-BACK MATERIAL, ⅜-INCH MAXIMUM SIZE AGGREGATE						
10-percent limestone dust as filler	11.6	1	0		131	
	11.9	1	7	1.2	108	82
	11.9	7	0		199	
		7	7	.7	181	91
10-percent clay as filler	11.9	1	0		236	
		1	7	3.9	77	33
	12.4	7	0		311	
	12.4	7	7	3.6	162	52
3-percent clay and 7-percent limestone dust as filler	11.6	1	0		155	
	11.9	1	7	3.6	119	77
	11.2	7	0		256	
	11.2	7	7	1.4	183	71
10-percent clay as film on particles	13.6	1	0		257	
	13.2	1	7	7.0	31	12
	14.0	7	0		306	
	14.0	7	7	5.3	66	22
7-percent clay as film on particles, 3-percent limestone dust as filler	13.6	1	0		203	
	13.6	1	7	6.1	25	12
	13.6	7	0		282	
	13.2	7	7	5.2	41	15
3-percent clay as film on particles, 7-percent limestone dust as filler	11.9	1	0		155	
	11.9	1	7	2.5	60	39
	12.4	7	0		232	
		7	7	1.7	114	49
MC-3 CUT-BACK MATERIAL, ¾-INCH MAXIMUM SIZE AGGREGATE						
9-percent limestone dust as filler	4.9	1	0		65	
		1	7	0.2	63	97
		7	0		97	
	5.3	7	7	0	123	127
9-percent clay as filler	5.3	1	0		161	
	5.3	1	7	4.6	30	19
		7	0		220	
		7	7		70	31
8-percent clay as film on particles, 1-percent clay as filler	6.2	7	0		252	
	6.7	7	7	5.0	26	10

tained stability. It was found that the compressive strength of the dry specimens containing clay was higher than that of similar specimens containing limestone filler.

The influence of time of curing on loss of stability is seen by comparing the stability losses of specimens in each mixture group representing the two oven-curing periods.

In general, a very consistent relation is evident between the swell of the specimens and the proportions of clay. As the percentage of clay was increased, the volume change increased, with the greater changes indicated by the mixtures containing clay as a coating on the aggregate particles than in those containing clay as a filler.



SPECIMENS TESTED DRY WERE BROUGHT TO TEST TEMPERATURE IN THIS INSULATED AIR CHAMBER

A STUDY OF WIDER SCOPE PLANNED

The usefulness of an immersion-compression test having been demonstrated within the limits of the two investigations described above, it was decided to determine the value of the test more completely by a study of considerably larger scope. Bituminous mixtures were selected with the view of throwing light on the following:

(1) The advantage of this type of test over the less direct stripping test now in general use.

(2) The sensitivity of the test to minor variations in the hydrophilic properties of the aggregate.

(3) The usefulness of the test in evaluating various types of filler material.

(4) The usefulness of the test in indicating variations in the quality of dense mixtures.

(5) The usefulness of the test in indicating the effect on mixture quality of various grades of asphaltic material.

Three bituminous materials were used—an 85–100 penetration asphalt, an MC–3 cut-back asphalt, and an RC–4 cut-back asphalt. The more important characteristics of these materials are shown in table 7. In all mixtures the bitumen content was 6 parts of bitumen to 100 parts of aggregate, by weight.

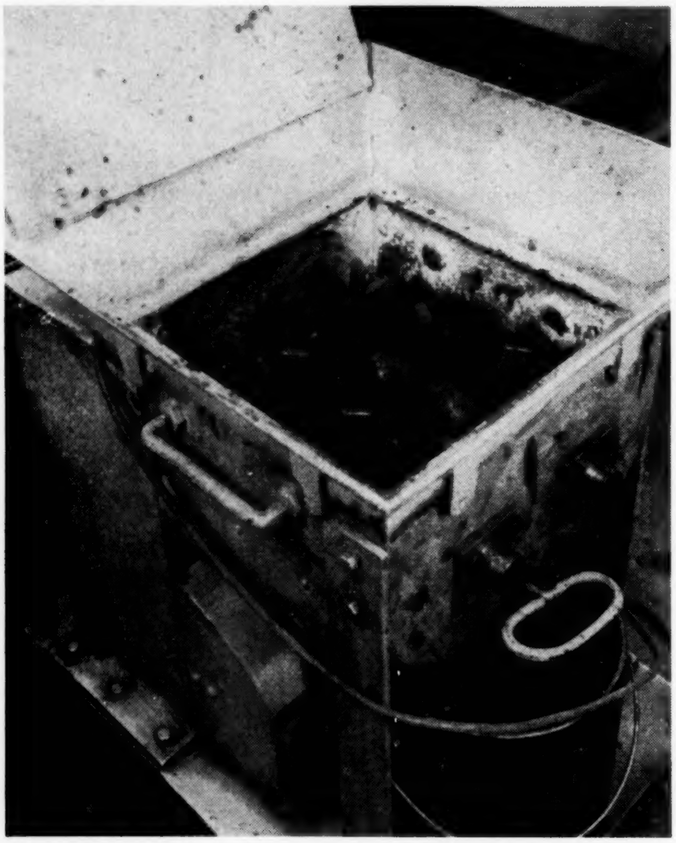
Four types of coarse aggregate were used—a crushed limestone (hydrophobic), a crushed quartzite (hydrophilic), a pit gravel (hydrophilic), and a river gravel (hydrophobic).

Three types of fine aggregate were used—river sand (hydrophobic), crushed limestone sand (hydrophobic), and crushed quartzite sand (hydrophilic).

TABLE 9.—*Characteristics of aggregates and fillers used*

Aggregates	Nature	Apparent specific gravity	Percent passing No. 200 sieve
Coarse aggregates:			
Crushed quartzite	Hydrophilic	2.63	
Crushed limestone	Hydrophobic	2.71	
Washed Potomac River gravel	do	2.64	
Washed pit gravel	Hydrophilic	2.64	
Fine aggregates:			
Washed Potomac River sand	Hydrophobic	2.64	2
Washed crushed quartzite	Hydrophilic	2.63	0
Washed crushed limestone	Hydrophobic	2.71	0
Fillers:			
Pulverized silica	Hydrophilic	2.64	100
Pulverized limestone	Hydrophobic	2.71	100
Pulverized clay [1]	Hydrophilic	2.67	100

[1] Liquid limit, 71; plasticity index, 46.



Mixtures For Compression Specimens Were Prepared in a Twin-Pugmill Mixer.

Table 10.—*Composition of aggregate blends*

Passing	7-percent filler blends	12-percent filler blends	Passing	7-percent filler blends	12-percent filler blends
	Percent	*Percent*		*Percent*	*Percent*
½-inch sieve	100	100	No. 10 sieve	37	42
⅜-inch sieve	66	69	No. 200 sieve	7	12
No. 4 sieve	42	47			

Three types of filler were used—pulverized limestone, pulverized silica, and pulverized New York Avenue clay. All fillers passed a 200-mesh sieve.

Selected combinations of these materials, and not all possible combinations, were used in the investigation. Characteristics of aggregates and fillers are given in table 9.

Two percentages of filler were used with each combination of coarse and fine aggregate. The composition of the aggregate blends by sizes is shown in table 10.

All mixtures were prepared in a laboratory twin-pugmill mixer of 20 pounds capacity. The mixer has electric heating elements to prevent excessive cooling during mixing.

In general, the mixing time, measured from the time all the bituminous material had been added to the discharge of the batch, was 1½ minutes. Mixtures containing clay filler required up to 2½ minutes for the production of a batch of uniform appearance. Prior to mixing, the bituminous materials were heated to the following temperatures: Asphalt cement, 300° F.; MC–3, 200° F.; RC–4, 225° F.

In preparing the mixtures containing asphalt cement, the aggregate was heated to a temperature of 325° F. before mixing. In the cut-back mixtures the aggregate was unheated. Temperature of the asphalt cement mixtures at the time of molding was 260° F., and the molds were heated to that temperature also. Molding of the cut-back mixtures was done at room temperature.

Table 11.—*Results of modified Nicholson stripping test on coarse fractions of aggregates used in immersion-compression test study*

Type of aggregate	Estimated area coated after 45 minutes of rotation; aggregate mixed with—		
	AC (85–100)	RC–4	MC–3
Quartzite	100	90	80
Limestone	100	100	100
River gravel	100	100	95
Pit gravel	100	100	85

Molding of the asphalt cement mixtures followed mixing immediately. Molding of the MC–3 and RC–4 mixtures followed 24 hours of curing at room temperature. All specimens were 4 inches in diameter and 4 inches in height, and were molded between double plungers under a load of 3,000 pounds per square inch, held for 2 minutes.

THE TEST PROCEDURE USED IN THE EXTENDED STUDY DESCRIBED

After molding, all specimens were placed in an oven maintained at a constant temperature of 140° F. After 24 hours in the oven they were removed and allowed to stand overnight at room temperature. The second day after molding, the specimens were weighed in air and water for specific gravity and volume determinations. Three of the 12 specimens representing each mixture were then brought to test temperature (77° F.) and tested for compressive strength. At the same time, the other nine specimens were completely submerged in a water bath maintained at 77° F. They were tested for compressive strength in sets of three specimens at the end of 2, 4, and 7 days of immersion. Just prior to testing, each specimen was weighed in water, then surface dried and weighed in air, for the purpose of calculating absorption and volume change.

The compressive strength of all specimens was determined by means of a hydraulic testing machine, using a platen speed of 0.2 inch per minute, the specimens being free of lateral support. The results of the modified Nicholson test are given in table 11. The results of the immersion-compression test, and swell and absorption data, are given in table 12.

Concurrently with this study, a laboratory investigation was carried on to determine the effect of several additives in preventing stripping of bituminous coatings from aggregates. In addition to the Nicholson test, the immersion-compression test was used to measure the effect of these additives on the retention of stability by the mixtures. Although this work has not yet been completed, a portion of the data is included in this report as being of interest in further demonstrating the usefulness of the immersion-compression test. These data are shown in table 13.

RESULTS DEMONSTRATE USEFULNESS OF IMMERSION-COMPRESSION TEST IN DETERMINING EFFECT OF WATER ON MIXTURES

The use of selected aggregate gradings resulted in very high densities in the molded specimens. Regardless of the type of coarse aggregate used, the mixtures containing 12-percent limestone dust were denser than those containing the same quantity of either of the other fillers. In the mixtures with 7-percent filler, however,

TABLE 12.—*Results of immersion-compression tests on specimens containing hydrophilic and hydrophobic aggregates*

ASPHALT CEMENT (85–100)

Time of immersion	QUARTZITE AND POTOMAC RIVER SAND								LIMESTONE AND POTOMAC RIVER SAND							
	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained
Days	*Percent*	*Percent*	*Lb per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*
Silica dust, percent	7				12				7				12			
Air voids, percent [1]	4.4				3.0				4.0				3.3			
None			252				348				261				295	
None			278				317				268				308	
None							346				246				306	
Average			265				337				258				303	
2	1.1	0.5	324		0.9	0.8	347		1.1	0.4	279		0.1	0.4	344	
2	1.0	.5	322		.3	.4	391		.1	.6	288		.1	.4	352	
2	.7	.4	352		.3	.3	374		.1	.4	312		.2	.5	353	
Average	.9	.5	333	126	.5	.5	371	110	.4	.5	293	114	.1	.4	350	116
4	.9	.5	364		.2	.5	344		.2	.6	300		.4	.5	369	
4	1.0	.7	296		.2	.4	342		.6	.9	303		.1	.6	386	
4	1.2	.7	345		.7	.7	333		.1	.6	325		.5	.8	370	
Average	1.0	.6	335	126	.4	.5	340	101	.3	.7	309	120	.1	.6	375	123
7	.7	1.0	267		.1	.4	337		.5	.7	295		.3	.5	333	
7	1.5	1.4	259		.5	.8	335		.6	.9	269		.2	.5	343	
7	1.2	1.3	257		.7	.9	341		1.2	1.1	284		.4	.6	338	
Average	1.1	1.2	261	98	.4	.7	338	100	.8	.9	283	110	.3	.5	338	112
Limestone dust, percent	7				12				7				12			
Air voids, percent [1]	3.5				2.6				3.7				2.0			
None			277				343				265				318	
None			298				349				253				299	
None							361				267				322	
Average			288				351				262				313	
2	1.2	0.6	338		0.4	0.5	357			0.4	308			0.3	378	
2	.7	.3	329		.2	.3	367			.4	318			.2	354	
2	.6	.2	346		.2	.4	365			.5	303			.3	372	
Average	.8	.4	338	117	.3	.4	363	103	0.1	.4	310	118	0.5	.3	368	118
4	1.4	.8	333		.5	.6	332			.4	287			.2	329	
4	1.5	.8	329		.7	.6	329			.5	266			.3	345	
4	.7	.6	285		.2	.4	331			.5	296			.4	342	
Average	1.2	.7	316	110	.5	.5	331	94	0	.5	283	108	.5	.3	339	108
7	.5		255		.1	.2	347		.4	.9	243		.1	.4	312	
7	.5	.8	269		.1	.3	319		.5	1.0	243		0	.5	306	
7	1.0	.8	263		.2	.5	328		1.5	1.5	241		0	.3	307	
Average	.7	.8	262	91	.1	.3	331	94	.8	1.1	242	92	0	.4	308	98
Clay dust, percent	7				12				7				12			
Air voids, percent [1]	3.1				3.2				2.5				2.6			
None			313				410				305				399	
None			298				404				344				408	
None			316				405				319				453	
Average			309				406				323				420	
2	0.2	0.5	329		0.5	0.7	395		0.2	0.4	377		0.2	0.5	424	
2	0	.6	330		1.0	1.0	384		.2	.5	372		.6	.7	427	
2	.6	.7	342		.9	1.0	382		.6	.6	378		.4	.6	427	
Average	.3	.6	334	108	.8	.9	387	95	.3	.5	376	116	.4	.6	426	101
4	.5	.6	349		.6	.8	403		.2	.5	370		.8	.7	450	
4	.5	.7	343		1.0	1.1	397		.2	.6	341		.4	.8	454	
4	1.0	1.1	330		2.1	1.5	356		.5	.6	363		.9	.9	442	
Average	.7	.8	341	110	1.2	1.1	385	95	.3	.6	358	111	.7	.8	449	107
7	.5	.6	349		.8	1.0	354		.4	.5	341		.8	.7	387	
7	.8	.8	341		1.4	1.2	366		.4	.6	308		1.1	.8	411	
7	1.1	1.0	335		1.5	1.3	353		.5	.7	327		.5	.9	389	
Average	.8	.8	342	111	1.2	1.2	358	88	.4	.6	325	101	.8	.8	396	94

See footnotes at end of table.

TABLE 12.—*Results of immersion-compression tests on specimens containing hydrophilic and hydrophobic aggregates*—Continued

RC-4 CUT-BACK ASPHALT

Time of immersion	QUARTZITE AND POTOMAC RIVER SAND								LIMESTONE AND POTOMAC RIVER SAND							
	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained
Days	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*
Silica dust, percent			7				12				7				12	
Air voids, percent [1]			3.8				2.7				2.6				2.2	
None			110				108				105				128	
None			107				118				108				123	
None			111				111				106				124	
Average			109				112				106				125	
2	0.6	0.9	96		0.6	0.9	96		0.3	0.6	95		0.8	0.9	106	
2	.5	1.0	96		.6	1.0	97		.3	.7	84		.8	1.0	112	
2	.4	.9	101		.5	.8	92		.2	.6	87		.9	.9	110	
Average	.5	.9	98	90	.6	.9	95	85	.3	.6	89	84	.8	.9	109	87
4	.6	1.1	76		2.0	1.7	73		.3	1.0	78		1.3	1.1	97	
4	.7	1.1	86		1.8	1.5	76		.8	1.0	74		.9	1.1	97	
4	.5	1.2	82		2.0	1.7	70		.7	.9	78		1.1	1.1	100	
Average	.6	1.1	81	74	1.9	1.6	73	65	.6	1.0	77	73	1.1	1.1	98	78
7	1.3	1.4	72		5.4	3.2	25		1.2	1.4	61		1.7	1.5	72	
7	1.3	1.6	72		4.8	2.8	32		1.6	1.4	57		2.0	1.6	63	
7	1.1	1.6	74		4.3	2.7	39		1.8	1.3	57		1.8	1.4	70	
Average	1.2	1.5	73	67	4.8	2.9	32	29	1.5	1.4	58	55	1.8	1.5	68	54
Limestone dust, percent			7				12				7				12	
Air voids, percent [1]			3.4				2.3				2.1				1.5	
None							116				101				104	
None			109				121				105				105	
None			105				111				101				102	
Average			107				116				102				104	
2	0.3	0.8	95		0.3	0.6	103		0.6	0.6	101		0.5	0.6	107	
2	0	.7	95		.3	.6	112		.6	.6	104		.3	.6	112	
2	.5	1.0	85		.1	.7	113		.6	.7	96		.4	.6	105	
Average	.3	.8	92	86	.2	.6	109	94	.6	.6	100	98	.4	.6	108	104
4	.7	1.1	87		.5	.7	98		.6	.8	98		.6	.9	112	
4	.4	1.0	90		.5	.9	110		.5	.7	103		.4	.6	105	
4	.6	1.1	87		.3	.9	107		.6	.8	99		.5	.6	112	
Average	.6	1.1	88	82	.4	.8	105	90	.6	.8	100	98	.5	.7	110	106
7	.7	1.2	79		.5	1.0	94		.4	.8	93		.3	.7	106	
7	.8	1.1	81		.7	1.0	89		.5	.8	100		.5	.7	105	
7	.4	1.2	89		1.0	1.3	89		.5	.8	99		.4	.6	103	
Average	.6	1.2	83	78	.7	1.1	91	78	.5	.8	97	95	.4	.7	105	101
Clay dust, percent			7				12				7				12	
Air voids, percent [1]			2.6				3.1				1.5				1.8	
None			171				251				142				219	
None			180				252				152				242	
None			182				259				147				249	
Average			178				254				147				237	
2	1.0	1.0	140		1.4	1.7	163		1.3	1.0	107		2.2	1.7	127	
2	1.1	1.2	142		1.4	1.5	175		1.0	.8	104		1.9	1.5	139	
2	.8	1.1	145		1.8	1.8	161		.9	.9	117		2.9	2.1	109	
Average	1.0	1.1	142	80	1.5	1.7	166	65	1.1	.9	109	74	2.3	1.8	125	53
4	1.0	1.1	134		2.3	2.1	139		1.7	1.2	92		3.7	2.2	85	
4	1.4	1.4	126		2.3	2.0	143		1.7	1.2	97		3.8	2.2	83	
4	1.0	1.2	135		3.4	2.6	125		2.0	1.3	95		6.1	2.9	67	
Average	1.1	1.2	132	74	2.7	2.2	136	54	1.8	1.2	95	65	4.5	2.4	78	33
7	1.9	1.7	109		3.5	2.6	99		2.9	1.7	64		10.6	5.0	19	
7	1.9	1.6	111		3.3	2.6	103		2.6	1.6	68		10.2	4.9	8	
7	2.2	1.8	109		4.8	3.4	84		2.7	1.6	64		12.2	6.1	11	
Average	2.0	1.7	110	62	3.9	2.9	95	37	2.7	1.6	65	44	11.0	5.3	13	5

See footnotes at end of table.

TABLE 12.—*Results of immersion-compression tests on specimens containing hydrophilic and hydrophobic aggregates*—Continued

MC-3 CUT-BACK ASPHALT

Time of immersion	QUARTZITE AND POTOMAC RIVER SAND								LIMESTONE AND POTOMAC RIVER SAND							
	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strengh retained	Swell	Water absorbed	Compressive strength	Strength retained
Days	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*
Silica dust, percent			7				12				7				12	
Air voids, percent [1]			3.7				3.1				2.4				1.4	
None			34				49				36				51	
None			25				53				39				47	
None			26				47				32				53	
Average			32				50				36				50	
2	0.8	1.1	31		1.0	1.2	48		0.2	0.5	29		0.5	0.6	43	
2	.8	1.2	37		.4	.9	50		.5	.6	32		.3	.5	47	
2	.9	1.3	30		1.2	1.4	49		.4	.6	31		.6	.6	42	
Average	.8	1.2	33	103	.9	1.2	49	98	.4	.6	31	86	.5	.6	44	88
4	1.5	1.6	21		2.4	2.0	27		.3	.9	24		2.2	1.3	27	
4	1.2	1.5	21		1.8	1.6	33		.7	.8	24		1.9	1.2	27	
4	1.4	1.5	21		1.9	1.8	29		.8	.9	25		2.2	1.4	23	
Average	1.4	1.5	21	66	2.0	1.8	30	60	.6	.9	24	67	2.1	1.3	26	52
7	(2)	(2)	(2)		6.1	3.5	7		2.6	1.8	14		7.3	3.5	8	
7	2.7	2.2	12		5.9	3.5	8		2.1	1.6	15		(3)	(2)	9	
7	2.9	2.3	11		5.1	2.9	11		2.4	1.7	17		10.0	4.6	11	
Average	2.8	2.2	12	38	5.7	3.3	9	18	2.4	1.7	15	42	8.6	4.0	9	18
Limestone dust, percent			7				12				7				12	
Air voids, percent [1]			3.3				2.5				1.7				0.8	
None			47				51				39				41	
None			32				51				34				45	
None			37				49				35				43	
Average			39				50				36				43	
2	0.2	0.8	37		0.2	0.4	55		0	0.3	34		0	2.0	50	
2	.2	.7	35		.2	.6	51		0	.2	36		0	1.9	42	
2	.2	.8	37		.4	.5	52		0	.2	35		0.1	1.6	46	
Average	.2	.8	36	92	.3	.5	53	106	0	.2	35	97	0	1.8	46	107
4	.6	1.0	33		.1	.6	51		0	.4	40		0	2.0	46	
4	.6	1.0	34		.7	.8	43		0	.4	33		0	2.3	45	
4	.5	1.0	35		.2	.7	44		0	.4	37		0	2.0	50	
Average	.6	1.0	34	87	.3	.7	46	92	0	.4	37	103	0	2.1	47	109
7	.7	1.2	28		.2	.7	50		0	.5	35		0	2.2	45	
7	.6	1.2	32		.3	.8	44		0	.4	30		0	2.2	47	
7	.5	1.0	34		.6	.9	50		0	.4	34		0	2.8	44	
Average	.6	1.1	31	79	.4	.8	48	96	0	.4	38	92	0	2.4	45	105
Clay dust, percent			7				12				7				12	
Air voids, percent [1]			2.8				2.5				1.1				1.5	
None			72				127				66				93	
None			72				125				67				96	
None			70				127				66				95	
Average			71				126				66				95	
2	0.2	0.6	62		1.6	1.3	89		0.4	0.5	53		0.2	0.7	49	
2	.2	.6	58		1.2	1.2	90		.6	.5	57		1.7	1.2	51	
2	.4	.6	64		1.6	1.4	83		.7	.5	53		1.2	.9	55	
Average	.3	.6	61	86	1.5	1.3	87	69	.6	.5	54	82	1.0	.9	52	55
4	1.1	1.1	43		1.8	1.4	71		1.2	.8	37		4.5	2.2	28	
4	1.3	1.0	42		2.1	1.6	67		1.3	.8	41		4.1	2.0	28	
4	1.2	1.1	41		1.7	1.5	74		1.0	.9	37		4.7	2.3	26	
Average	1.2	1.1	42	59	1.9	1.5	71	56	1.2	.8	38	58	4.4	2.2	27	28
7	2.0	1.4	33		3.4	2.3	50		2.3	1.2	29		13.3	5.4	(2)	
7	1.9	1.5	33		1.9	2.1	49		2.7	1.4	25		17.6	10.9	10	
7	2.2	1.6	35		2.5	1.8	56		3.3	1.7	21		19.4	11.2	9	
Average	2.0	1.5	34	48	2.6	2.1	52	41	2.8	1.4	25	38	16.8	9.2	6	6

See footnotes at end of table.

655224—45——2

TABLE 12.—*Results of immersion-compression tests on specimens containing hydrophilic and hydrophobic aggregates*—Continued

MC-3 CUT-BACK ASPHALT

Time of immersion	PIT GRAVEL AND POTOMAC RIVER SAND				POTOMAC RIVER GRAVEL AND POTOMAC RIVER SAND				CRUSHED QUARTZITE AND QUARTZITE SAND				CRUSHED LIMESTONE AND LIMESTONE SAND			
	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strength retained	Swell	Water absorbed	Compressive strength	Strengh retained	Swell	Water absorbed	Compressive strength	Strength retained
Days	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Percent*
Silica dust, percent			12				12				12				12	
Air voids, percent [1]			3.9				3.4				3.3				1.4	
None			45				37				66				62	
None			54				39				68				62	
None			43				33				70				63	
Average			47				36				68				62	
2	1.6	1.6	33		0.9	1.2	38									
2	1.2	1.5	37		.8	1.1	38									
2	1.0	1.4	35		.8	1.0	38									
Average	1.3	1.5	35	74	.8	1.1	38	106								
4	4.4	2.9	10		1.7	1.6	24		7.3	4.0	8		3.2	1.7	33	
4	4.0	2.8	11		1.1	1.4	25		5.7	3.3	14		3.1	1.7	35	
4	3.6	2.6	14		2.0	1.7	23		6.0	3.3	11		3.0	1.6	33	
Average	4.0	2.8	12	26	1.6	1.6	24	67	6.3	3.5	11	16	3.1	1.7	34	55
7	[2]	[2]	[2]		4.7	3.0	8		[2]	[2]	[2]		6.4	3.0	16	
7	[2]	[2]	[2]		3.6	2.6	13		[2]	[2]	[2]		7.1	3.4	13	
7	[2]	[2]	[2]		4.1	2.6	10		[2]	[2]	[2]		8.0	3.8	16	
Average				0	4.1	2.7	10	28				0	7.2	3.4	15	24
Limestone dust, percent			12				12				12				12	
Air voids, percent [1]			3.4				2.5				2.9				1.3	
None			44				43				70				62	
None			45				42				69				60	
None			41				43				64				56	
Average			43				43				68				59	
2	0.7	1.1	45		0	0.4	42									
2	.2	.9	41		0.4	.2	43									
2	.4	.9	46		.3	.3	45									
Average	.4	1.0	44	102	.2	.3	43	100								
4	.6	1.1	41		.3	.6	38		0.3	0.9	56		0	0.3	72	
4	.6	1.0	47		0	.4	45		.3	.8	56		0	.3	73	
4	.8	1.1	42		.1	.2	44		0	.7	60		0	.3	69	
Average	.7	1.1	43	100	.1	.4	42	98	.2	.8	57	84	0	.3	71	120
7	.8	1.2	34		.1	.7	40		.5	1.0	51		0	.4	64	
7	.9	1.1	41		0	.6	44		.7	1.0	47		.2	.4	62	
7	1.1	1.4	33		.1	.6	41		.1	.8	57		0	.4	60	
Average	.9	1.2	36	84	.1	.6	42	98	.4	.9	52	76	.1	.4	62	105
Clay dust, percent			12				12				12				12	
Air voids, percent [1]			3.7				3.1				2.3				1.5	
None			129				108				134				111	
None			121				120				131				114	
None			120				113				136				109	
Average			123				114				134				111	
2	3.7	2.8	45		1.0	1.2	77									
2	2.6	2.2	49		.7	1.0	90									
2	2.7	2.5	48		.4	.9	88									
Average	3.0	2.5	47	38	.7	1.0	85	74								
4	5.9	3.5	24		2.3	2.0	53		3.4	1.9	58		6.7	2.9	24	
4	4.3	2.8	32		2.3	2.1	53		3.8	2.1	51		8.1	3.5	21	
4	5.6	3.4	26		1.6	1.7	60		4.3	2.3	45		9.2	3.9	19	
Average	5.3	3.2	27	22	2.1	1.9	55	48	3.8	2.1	51	38	8.0	3.4	21	19
7	13.5	6.4	10		5.9	3.8	22		13.5	5.9	13		21.0	8.8	8	
7	14.2	6.8	8		4.1	2.7	35		10.9	4.7	22		[2]	[2]	[2]	
7	12.2	5.8	10		4.0	2.6	32		[2]	[2]	[2]		[2]	[2]	[2]	
Average	13.3	6.3	9	7	4.7	3.0	30	26	12.2	5.3	12	9			3	3

[1] Air voids in compacted specimens.

[2] Specimen disintegrated in water bath.

the clay filler produced the highest density. As between the stone mixtures and the gravel mixtures, the gravel mixtures were less dense. Mixtures containing crushed limestone produced higher densities than those containing crushed quartzite, when comparable percentages of the three respective fillers were used.

As would be expected, the stabilities of dry specimens representing all aggregate and filler groups reflected directly the consistency of the bituminous material used. That is, for any type of coarse aggregate containing the same percentage of any of the three fillers, stabilities were highest in specimens containing asphalt cement, lowest in those containing MC–3 material, with intermediate values for those containing RC–4 material.

For any given grade of bituminous material and for comparable percentages and types of filler, the mixtures containing quartzite as coarse aggregate generally had higher stabilities than those containing limestone. This may be explained by the rougher surface texture of the quartzite. In the mixture groups containing limestone and quartzite as coarse aggregate, increasing the percentage of filler from 7 to 12 invariably resulted in stability increases in the dry specimens ranging from as low as 2 percent for mixtures of crushed limestone, RC–4 material, and limestone filler to 77 percent for the mixtures of quartzite, MC–3 material, and clay filler. Dry specimens containing clay filler had higher stabilities than comparable specimens containing either limestone or silica fillers.

It was observed that in many of the mixtures containing asphalt cement the specimens that had been immersed in water had higher stability values than corresponding dry specimens. In future work with such mixtures, a period of immersion in water in excess of 7 days will be used, with the expectation of developing more rational information.

This same phenomenon was also observed in several of the mixtures with MC–3 and RC–4 materials after 2 days immersion. Since it does not appear that the character of the aggregates, of itself, is responsible for this apparent increase in stability, the values from specimens immersed only 2 days will be disregarded in discussing the data. Results of the tests on mixtures containing the MC and RC materials, expressed in terms of percentage of stability retained after immersion, are shown graphically in figures 1, 2, and 3.

The effect of immersion in water on mixtures with RC–4 material is shown in figure 1, the data being from table 12. For easy comparison, the curves representing mixtures containing quartzite and the three fillers and those containing limestone and the three fillers have been arranged side by side. Considering first the effect of the character of the filler only on the quartzite mixtures, it is apparent that 7-percent clay produces a greater loss in stability than the same percentage of either of the other fillers, with the 7-percent limestone dust mixture showing the least reduction. With increased percentage of the respective fillers, the greatest loss is produced by the silica, and the least loss again is shown by the limestone dust.

In the case of the limestone mixtures with either percentage of fillers limestone filler produced little or no loss with the clay filler showing the greatest loss.

The stabilities of the quartzite and limestone mixtures containing comparable percentages of the three fillers are not entirely in accord with what would be expected from the results of the stripping tests on the

TABLE 13.—*Effect of additives in reducing loss of strength in 4- by 4-inch cylinders as indicated by immersion-compression and stripping tests*

Additives used with MC–2 [1] cut-back asphalt	Coarse aggregate (½-inch–No. 10) [2]	Water absorbed after 4 days in water	Volumetric swell after 4 days in water [3]	Compressive strength: Dry [4]	Compressive strength: After immersion 4 days in water	Strength retained after 4 days in water	Stripping test,[5] area coated
		Percent	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Percent*
None	Trap			57	0	0	80
	Granite	3.8	4.6	62	17	27	60
	Limestone	1.6	1.7	56	39	70	100
Additive A, 1-percent	Trap	2.0	0	60	62	103	95
	Granite	1.5	.6	59	57	97	95
	Limestone	.8	.3	50	56	112	100
Additive B, 0.65-percent	Trap	2.0	1.0	65	45	69	100
	Granite	1.6	1.1	64	53	83	100
	Limestone	.6	0	51	60	118	100
Additive C, 0.5-percent	Granite	1.9	1.4	62	43	69	95
	Limestone	.8	.1	49	53	108	100
Additive D, 1-percent	Granite	1.5	.6	59	57	97	95
	Limestone	.8	.3	50	56	112	100
Additive E, 2-percent	Granite	1.4	.4	61	55	90	95
	Limestone	.6	0	49	51	104	100
Additive F, 2-percent	Granite	1.4	1.1	66	49	75	90
	Limestone	.7	.2	48	49	102	95

[1] Important characteristics shown in table 7.
[2] Composition of mixture: Coarse aggregate, 60 percent; fine aggregate, river sand, 30 percent; filler, silica, 10 percent.
[3] Cylinders immersed in water at 77° F. after curing.
[4] Cylinders tested after curing for 24 hours at 140° F.
[5] Modified Nicholson test on coarse aggregate, condition at end of 45 minutes.

coarse aggregates. It is only in the mixtures containing limestone filler that results consistent with the stripping properties of the coarse aggregates were obtained. Mixtures containing limestone and limestone filler in either percentage weakened considerably less than those containing quartzite stone and limestone filler. On the other hand, 7 percent of silica dust in combination with quartzite stone showed less loss than a corresponding percentage of silica dust with limestone coarse aggregate. However, the loss shown by 12 percent of silica dust with quartzite was considerably greater than that shown by the comparable mixture in which limestone was used as the coarse aggregate. It is possible that the disparity in proportional effect as between the two percentages of silica filler in combination with the two coarse aggregates may be due to experimental error. Comparison of the quartzite-clay and the limestone-clay mixtures shows that clay produces much greater loss with limestone than with quartzite.

The stability retained by mixtures of quartzite, river sand, and the three fillers combined with MC–3 material in relation to that of corresponding mixtures in which the coarse aggregate is limestone, is also shown in figure 1. The data are from table 12. Considering only the effect of the various fillers, in the quartzite mixtures the highest loss was produced by the silica filler and the lowest by the limestone filler. In the limestone mixtures however clay produced the greatest loss with limestone dust the least. Comparing quartzite with limestone mixtures containing corresponding types of filler, it is seen that the hydrophobic property of the limestone did contribute slightly to the retention of stability by the mixtures containing silica or limestone fillers but this is not true of the mixtures containing clay.

The effect of water on mixtures containing gravel and the three fillers is seen in figure 2, based on the data of table 12. As stated previously, the Potomac River gravel is considered to be hydrophobic and the pit gravel to be hydrophilic. Results of the immersion-

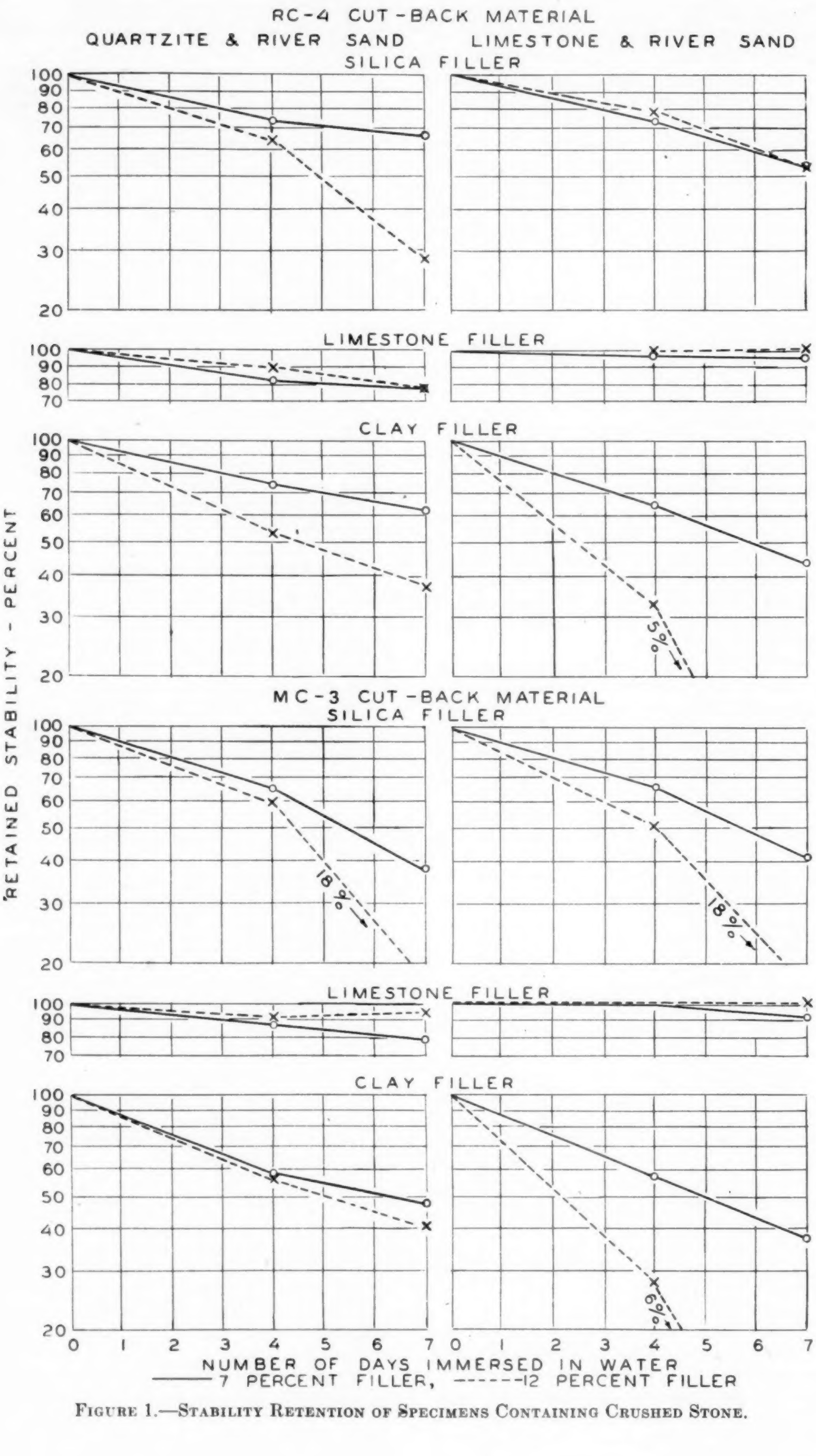


FIGURE 1.—STABILITY RETENTION OF SPECIMENS CONTAINING CRUSHED STONE.

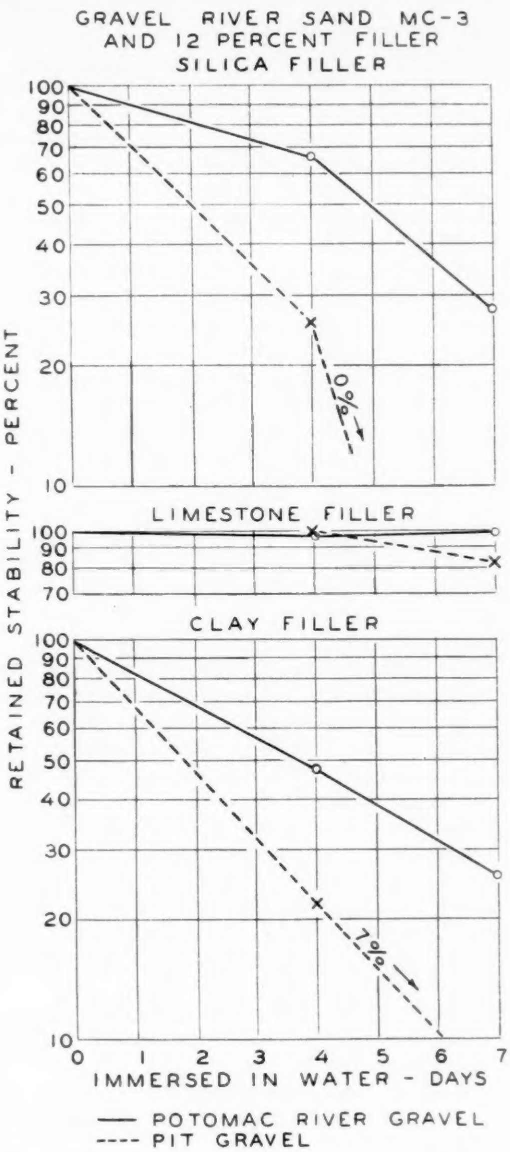


FIGURE 2.—STABILITY RETENTION OF SPECIMENS CONTAINING GRAVEL.

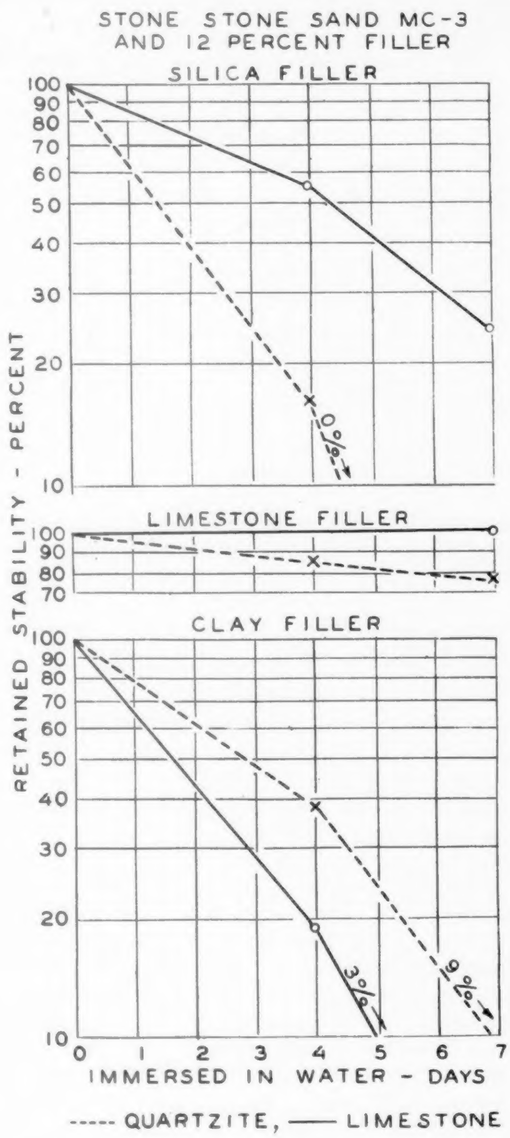


FIGURE 3.—STABILITY RETENTION OF SPECIMENS CONTAINING CRUSHED STONE SAND FRACTION.

compression test seem to corroborate this distinction. However, judging from the test results on the mixtures with limestone filler the effect of variation in the coarse aggregate fraction is comparatively small. Different types of filler, however, cause large differences in rates of loss of stability. In pit gravel mixtures silica filler produced the greatest loss and limestone filler the least, while in the Potomac River gravel mixtures the losses at 7 days for silica and clay fillers were only slightly different.

In most of the mixtures studied, the fine aggregate consisted of washed Potomac River sand, which is considered to be hydrophobic, although it is difficult if not impossible to evaluate this property in fine aggregate fractions with the commonly used stripping tests.

In order to obtain a more positive indication of the influence of the nature of the fine aggregate, mixtures were made in which the fine aggregate was prepared by crushing the same stone that composed the coarse aggregate. The data from tests of the mixtures are shown in table 12 and figure 3. In the quartzite group, the mixtures containing silica filler disintegrated completely in the water bath before the 7-day immersion period had elapsed. With quartzite aggregate the clay-filler mixtures had lost most of their stability at the end of 7 days immersion, while those with limestone filler lost 24 percent. In the limestone group, water caused most damage to the clay-filler specimens, less to the silica-filler mixtures, and none at all to the limestone-filler mixtures.

From the meager data of these exploratory tests, no definite conclusions regarding the effect of the character of the sand fraction can be drawn. Direct comparison of mixtures containing crushed stone sand and those containing river sand is not possible due to the impracticability of exactly duplicating the grading of the river sand by crushing stone. Gradings representative of these sands are shown in table 14.

In the study of antistripping additives with particular aggregates entirely different indications were implied by results of the stripping test and the immersion-compression test (table 13). For example, in the tests of mixtures in which no additives were used, the Nicholson test showed limestone to be least affected by water and trap rock to be next best. In the immersion-compression test, while the limestone mixture lost only 30

TABLE 14.—*Gradation of sand fractions*

Sieve No.	Potomac River sand	Quartzite	Limestone
	Percent passing	*Percent passing*	*Percent passing*
4	100	100	100
10	99	99	100
20	90	49	39
30	77	36	25
40	58	26	15
50	34	18	9
80	16	8	3
100	12	6	2
200	2	0	0

percent of its strength, the trap-rock mixtures lost all stability after 4 days in water.

As another example, in the tests with additive B, the Nicholson test showed all aggregates to be completely coated, whereas the immersion-compression test shows considerable difference in the behavior of mixtures containing each of the three stones. Also, the Nicholson test indicates that all five additives produced essentially equal improvement of coating on the granite, whereas the immersion-compression test shows that, while all the additives improved the retention of stability of the granite mixtures, the degree of improvement effected by the several additives differed considerably.

SUMMARY

Results of the studies described in this report indicate that an immersion-compression test, carried out in conformity with the suggested procedure, will produce information valuable in various phases of bituminous mixture design. The test is useful in:

1. Determining the effect of the use of hydrophilic aggregate, whether coarse or fine, on the stability of the mixture when exposed to the action of water. It is impractical to use the usual stripping tests in evaluating sands or fillers, yet results of the foregoing studies show the importance of fillers in the behavior of the whole mixture. It has been shown that satisfactory retention of stability may be developed in mixtures containing hydrophilic aggregate, provided suitable filler is used.

2. The selection of fillers with regard to their contribution to retention or loss of stability of the mixture in the presence of water.

3. The detection of aggregates that are structurally unsound when wet.

4. Determining the usefulness of additives in causing resistance to stripping of bituminous films from aggregate particles by water action.

5. Determining the minimum proportions of imported hydrophobic material required to reduce stability loss in the presence of water, in cases where local aggregate is found to be hydrophilic.

6. Testing aggregates considered for use in related types of construction, such as surface treatments. Although the primary value of the test is in the solution of problems in design of bituminous mixtures, it is believed that adaptations of the test would be useful in other bituminous work.

DETAILS OF TEST PROCEDURE

A complete description of a suggested test procedure follows:

1. The bituminous mixture for use in the test shall be composed of the aggregates, filler, and bituminous material in the proportions proposed for use in the actual construction. This is important, for it has been demonstrated that variations in aggregate, filler, or bituminous material result in corresponding differences in loss of stability.

2. Hot mixtures shall be molded immediately after mixing. All other mixtures shall be cured loose in air for 24 hours before molding. It has been found that such a curing period is necessary in order to obtain consistent results.

3. Cylindrical specimens 4 inches in diameter by 4 inches in height shall be molded under a load of 3,000 pounds per square inch by the double plunger method. Other means of compaction that will produce equally satisfactory results may be used. At least six specimens shall be molded for each mixture to be tested.

There is considerable diversity of opinion as to the proper relation of height to diameter of cylindrical specimens for compression testing. Some investigators hold that the influence of end effects may not be eliminated by the use of height-diameter ratios less than 2 to 1. Other workers report entirely consistent results with lower ratios when the specimens are tested between rubber disks. The importance of end effect in certain types of testing where absolute values are required is unquestioned, but, it is believed that for immersion-compression testing, where results are expressed in percentage of stability loss, the question as to the influence of end effects may be waived in the interest of convenience and practicability. In the development of the test procedure, several specimens 4 inches in diameter and 8 inches in height were tested under the same conditions and at the same time as other specimens of the same diameter and 4 inches in height. Although indicated compressive strengths of the two sets of specimens differed considerably, the percentage losses in stability checked quite well. The larger specimens were difficult to mold, and were much more susceptible to damage in the necessary handling incident to weighing and testing.

On the other hand, a specimen smaller than 4 inches by 4 inches would not be satisfactory for mixtures containing coarse aggregates.

4. All molded specimens shall be cured for 24 hours in an oven maintained at a uniform temperature of 140° F.

Freshly mixed and compacted roadway surfaces are immediately subjected to water action only in exceptional cases. Immersion of freshly molded specimens in the laboratory would result in greatly exaggerated effects.

5. After oven curing, the specimens shall be allowed to cool to laboratory temperature, then weighed in air and water for density and volume determinations.

6. Three of the six specimens shall then be tested in compression at room temperature after having been brought to a temperature of 77° F. in an air bath. The other three specimens shall be submerged in water at a temperature of 77° F. for a period of 4 days, after which they shall be removed from the water, weighed in air and water for moisture and volume determinations, and tested in compression.

In the work reported here, the specimens were placed on glass or aluminum plates in the water bath. These plates were found to be very convenient in preventing spalling or distortion in handling those specimens that became softened in the water bath.

Immersion for 4 days is recommended as productive of consistent and significant results in testing mixtures containing liquid asphalt materials. In testing hot mixtures, a longer immersion period will be required.

7. All specimens shall be tested in compression without lateral confinement, and at a rate of vertical deformation of 0.2 inch per minute.

This testing speed is in conformity with previous work of a similar nature.

It will be necessary to obtain much more data correlating service behavior with laboratory test results before test limits can be assigned for specification purposes. However, based on the work already done, it is believed that mixtures retaining not less than 75 percent of the dry stability after immersion for 4 days may be expected to have satisfactory resistance to water in service.

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ADDITIVES FOR BITUMINOUS MATERIALS

BY THE DIVISION OF PHYSICAL RESEARCH, PUBLIC ROADS ADMINISTRATION

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THE DETRIMENTAL EFFECT OF MOISTURE upon the service behavior of bituminous surfaces has long been a concern of engineers and, recently, attempts have been made to determine the basic causes of unsatisfactory behavior and to develop remedies. On this subject there is rather general agreement that:

(*a*) Aggregates vary considerably in their resistance to coating with bituminous materials and in their resistance to the loss of such coating in the presence of moisture.

(*b*) These variations are due to the character of both the aggregates and the bituminous materials.

(*c*) Chemical agents can be used to obtain a coating of bitumen and to increase its resistance to stripping.

PROPERTIES OF MATERIALS USED IN TESTS DESCRIBED

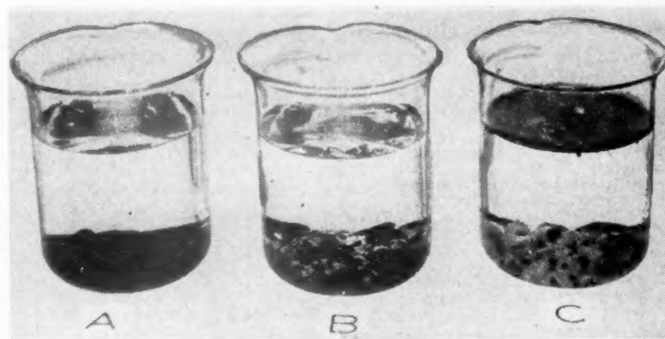
A number of chemical agents are being produced commercially and offered as aids in coating wet aggregate and in coating and the retention of coating on aggregates that normally may be adversely affected by moisture. To determine the extent to which commercial products are beneficial a study has been made of a number of products to obtain definite information on the following:

1. Effect of additives in coating wet aggregates with bitumen.
2. Effect of additives in reducing film stripping.
3. Effect of varying percentages of additives.
4. Effect of additives upon the characteristics of the bituminous materials with which they are used.
5. Effect of additives when used with different bituminous materials.
6. Effect of additives in reducing loss of strength of bituminous mixtures due to the presence of moisture.
7. Permanency of benefit obtained by the use of additives.

No attempt has been made to include in this investigation all of the materials that may be available. There are included, however, a number of representative materials. They are designated in this report by the letters A, B, C, D, E, F, and G, respectively.

The additives were used as received and in accordance with the recommendation of the producer except as to the amount of additive used. They varied somewhat in consistency at room temperature but all were liquid when warmed slightly. All were combined directly with the bituminous material but in one case the treated material was used in combination with quicklime.

The objectives of this study did not include the development of an additive and consequently additives were not analyzed to determine their composition. However, it was considered important to determine to what extent an additive affects the characteristics of the bituminous materials, especially those characteristics that are limited by specifications. Combinations of additives and bituminous materials, therefore, were analyzed and such analyses are included herein.



EFFECT OF ADDITIVES ON THE RETENTION OF BITUMINOUS COATINGS IN THE PRESENCE OF MOISTURE: (*A*) WITH 2 PERCENT OF ADDITIVE, COMPLETE COATING WAS RETAINED; (*B*) 1 PERCENT OF ADDITIVE WAS ONLY PARTIALLY SATISFACTORY; AND (*C*) WITHOUT AN ADDITIVE THE BITUMINOUS COATING WAS ALMOST COMPLETELY STRIPPED.

The bituminous materials used were MC–2 cut-back asphalt, RC–2 cut-back asphalt, RT–5 road tar, and asphalt cement of 120 to 150 penetration.

Analyses of the three liquid materials with and without additives are given in tables 1, 2, and 3. Corresponding analyses of the asphalt cement were not made. It will be observed from those tables that the effect of additives upon the original characteristics of the bituminous materials, in general, is too slight to be of importance unless the characteristics of the untreated material are at or near the specification limits.

The results of the thin-film oven test, which is an accelerated weathering test, show that no detrimental effects attributable to the additive should be expected to develop as a result of oxidation in service. For all practical purposes, therefore, the chemical and physical effects of the additives on the acceptability or serviceability of the bituminous material with which they are used, may be disregarded.

The aggegates used in the investigation vary in their hydrophilic properties and include materials having a record of unsatisfactory service behavior with respect to film stripping. The following materials were used: Two gravels, designated herein as No. 1 and No. 2 respectively; two granites designated as No. 1 and No. 2, one quartzite, one limestone, one limerock, one trap rock. The physical properties of these aggregates are given in table 4.

It will be observed, by reference to the tables, that not all of the various combinations of additives and bituminous materials were used with all aggregates. However, it is believed that the data obtained are sufficient to provide the information sought in the investigation.

THREE DIFFERENT TESTS MADE ON MIXTURES

The procedure adopted for examining and comparing the different additives was to prepare bituminous mixtures with and without additives and to subject them to the action of water. The tests used were as follows:

The modified Oberbach test.—This is a static immersion test which was performed under the following conditions

TABLE 1.—*Analyses of MC–2 asphalt with and without additives* [1]

	Untreated asphalt, No. 62533	Identification and amount of additive in bituminous material (No. 62533)										Untreated asphalt, No. 64439	Identification and amount of additive in bituminous material (No. 64439)					
		A			B			C			G		D			E		F
		1 percent	2 percent	4 percent	1 percent	2 percent	4 percent	0.5 percent	1 percent	2 percent	0.65 percent		0.5 percent	1 percent	2 percent	2 percent	4 percent	2 percent
Specific gravity 77°/77° F	0.966	0.967	0.967	0.968	0.967	0.967	0.967	0.967	0.966	0.964	0.966	0.962	0.962	0.961	0.961	0.962	0.963	0.962
Flash point, °F	135			140			140	140	145	155	145	150	145	145	140	145	140	145
Furol viscosity at 140° F., seconds	145.9	142.0	140.3	136.3	143.8	141.0	140.7	145.0	135.5	122.2	132.6	163.0	159.8	157.8	150.0	152.2	144.0	153.8
Distillation:																		
Distillate percentage by volume of total distillate to 680° F.:																		
To 374° F	Trace	Trace	2.0	Trace	2.0	2.0	2.0	2.0	2.0	3.9	2.0	3.4	2.1	2.1	2.1	2.0	2.0	2.0
To 437° F	8.2	8.0	9.8	8.2	10.0	6.0	8.2	8.0	11.8	9.8	12.0	8.5	10.5	12.5	10.6	10.2	10.0	14.0
To 500° F	44.9	44.0	43.1	44.9	44.0	44.0	40.8	44.0	45.1	45.1	46.0	44.7	44.1	45.8	44.7	44.9	44.0	46.0
To 600° F	81.6	80.0	76.5	79.6	80.0	78.0	77.6	78.0	80.4	82.4	82.0	80.8	79.8	81.3	78.7	81.6	82.0	80.0
Residue, percentage by volume total sample less distillate recovered	75.0	75.0	74.5	75.5	75.0	75.0	75.5	75.0	74.5	74.5	75.0	76.5	76.2	76.0	76.5	75.5	75.0	75.0
Tests on residue:																		
Penetration at 77° F. 100 gm. 5 seconds	194	197	194	224	238	240	330	196	188	228	215	182	195	207	250	171	182	190
Ductility at 77° F. 5 centimeters per minute, centimeters	122	113	163	182	111	110	79	113	119	111	144	140	160	205	215	160	180	158
Total soluble in CCl_4, percent	99.92	99.89	99.86	99.81	99.92	99.91	99.92	99.96	99.95	99.94	99.94	99.87	99.93	99.96	99.96	99.94	99.96	99.94
Organic insoluble, percent	.05	.07	.05	.05	.04	.04	.04	.02	.03	.05	.06	.09	.06	.04	.04	.05	.04	.05
Inorganic insoluble, percent	.03	.04	.09	.14	.04	.05	.04	.02	.02	.01	0	.04	.01	0	0	.01	0	.01
Oliensis spot test	Neg.			Neg.			Neg.				Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Neg
Thin film oven tests at 325° F. of 50 milliliter samples:																		
5-hour test:																		
Loss in weight, percent	24.8	24.3	24.2	23.4	24.4	24.4	23.7	24.5	24.9	25.0	25.1	23.4	23.4	23.3	22.7	23.5	23.6	23.6
Residue penetration, 77° F., 100 gm., 5 seconds	65	63	64	77	72	78	102	74	81	97	74	58	68	74	107	70	78	80
Residue ductility, 77° F., 5 centimeters per minute, centimeters	206	214	203	200	238	228	233	183	140	176	231	240	208	50+	250+	137	215	203
10-hour test:																		
Loss in weight, percent	25.7	25.4	25.3	25.2	25.6	25.7	24.6	25.4	25.8	26.0	25.7	24.1	23.8	23.9	23.4	24.4	24.4	24.2
Residue penetration, 77° F., 100 gm., 5 seconds	39	39	39	43	41	43	47	44	48	56	41	37	42	44	58	40	46	46
Residue ductility, 77° F., 5 centimeters per minute, centimeters	78	78	64	46	110	123	110	95	137	162	95	78	140	165	218	45	90	100
15-hour test:																		
Loss in weight, percent	26.0	25.7	25.6	25.4	25.9	25.8	25.5	26.0	26.2	26.3	26.4	24.5	24.3	24.3	24.2	24.8	25.0	24.7
Residue, penetration at 77° F., 100gm, 5 seconds	30	28	27	27	31	32	32	32	34	41	31	28	29	30	38	31	34	32
Residue, ductility at 77° F., 5 centimeters per minute, centimeters	22	15	11	10	15	21	21	27	53	96	27	12	16	22	78	16	17	26

[1] Bituminous material No. 62533 was used in the stripping tests of all aggregates and in the compression tests of all aggregates excepting gravel No. 1 and granite No. 2 in which bituminous material No. 64439 was substituted.

TABLE 2.—*Analyses of RC–2 asphalt with and without additives*

	Untreated asphalt	Identification and amount of additive in bituminous material									
		B		C		D		E		F	G
		1 percent	2 percent	0.5 percent	1 percent	0.5 percent	2 percent	2 percent	4 percent	2 percent	0.65 percent
Specific gravity, 77°/77° F	0.962	0.963	0.963	0.961	0.960	0.963	0.962	0.962	0.962	0.962	0.962
Flash point, °F	90		95		95	95	90	95	95	90	95
Furol viscosity at 140° F., seconds	229.8	217.2	214.4	222.0	205.8	225.0	199.9	217.4	201.7	219.4	220.8
Distillation:											
Distillate, percentage by volume of total distillate to 680° F.:											
To 374° F	43.8	39.6	40.4	44.7	42.6	42.6	41.7	37.5	40.0	45.8	41.7
To 437° F	70.8	68.8	68.1	70.2	70.2	70.2	72.9	66.7	64.0	70.8	70.8
To 500° F	83.3	83.3	83.0	85.1	83.0	85.1	83.3	83.3	80.0	83.3	83.3
To 600° F	93.8	91.7	91.5	93.6	91.5	93.6	91.7	91.7	95.8	91.7	93.8
Residue, percentage by volume, total sample less distillate recovered	76.0	76.0	76.5	76.5	76.5	76.5	76.0	76.0	75.0	76.0	76.0
Tests on residue:											
Penetration, 100 gm., 77° F., 5 seconds	81	90	102	85	95	89	109	83	87	91	92
Ductility, 77° F., 5 centimeters per min., centimeters	250+	194	218	218	224	220	250+	225	195	250+	250+
Total soluble in CCl_4, percent	99.93		99.94		99.97	99.96	99.92	99.97	99.95	99.96	99.96
Organic insoluble, percent	.05		.04		.03	.04	.08	.03	.05	.04	.03
Inorganic insoluble, percent	.02		.02		0	0	0	0	0	0	.01
Thin film oven tests at 325° F. of 50 milliliter samples, 5-hour test:											
Loss in weight, percent	20.8	20.3	20.5	20.9	20.6	20.8	20.4	21.0	21.1	20.7	20.7
Residue, penetration, 77° F., 100 gm., 5 seconds	37	41	46	44	48	46	58	40	45	45	45
Residue, ductility, 77° F., centimeters	128	197	250+	160	150	250+	235	108	125	150	217

TABLE 3.—*Analyses of RT–5 tar with and without additives*

	Untreated	Identification and amount of additive in bituminous material										
		A			B			C			D	G
		1 percent	2 percent	4 percent	1 percent	2 percent	4 percent	0.5 percent	1 percent	2 percent	0.5 percent	0.65 percent
Specific gravity 25°/25° C	1.174	1.173	1.172	1.166	1.172	1.170	1.165	1.172	1.170	1.166	1.168	1.172
Specific viscosity, Engler, at 50° C	17.5	18.1	18.5	18.8	17.9	17.9	17.8	16.3	14.8	13.6	17.1	16.5
Bitumen soluble in CS_2, percent	89.42	89.07	89.34	89.51	89.21	89.45	90.03	89.22	89.03	89.21	88.95	88.67
Organic insoluble, percent	10.53	10.86	10.58	10.40	10.75	10.43	9.93	10.77	10.95	10.76	10.97	11.31
Inorganic insoluble, percent	.05	.07	.08	.09	.04	.12	.04	01	.02	.03	.08	.02
Distillation:												
Percentage by weight:												
To 170° C	Trace	Trace	Trace	Trace	Trace	Trace	Trace	.16	.30	0.41	Trace	Trace
170–235° C	3.68	4.04	3.14	4.01	3.20	4.04	2.23	3.49	3.96	4.33	3.67	3.61
235–270° C	10.20	9.22	10.44	10.08	9.55	10.04	8.57	9.08	9.12	9.57	8.68	10.11
270–300° C	9.03	8.96	8.56	9.71	9.06	8.51	12.05	9.03	9.44	9.13	9.00	8.60
Residue	76.13	77.37	76.95	75.60	78.00	76.90	76.80	77.78	77.03	76.14	78.20	77.20
Softening point of residue, ° C	34.8	34.4	34.7	36.3	34.1	34.4	34.5	32.4	33.0	33.1	33.5	34.6
Sulfonation index (0–300° C. fraction)	1.79	------	1.72	1.83	------	1.70	1.64	------	------	1.61	1.53	1.59
Thin film oven test, 50 milliliters, 163° C., 4 hours:												
Loss in weight, percent	28.6	27.8	26.5	25.7	28.3	27.6	27.2	28.0	28.3	28.4	28.6	28.3
Penetration at 25° C., 100 gm. 5 seconds	8	10	14	22	10	15	26	12	12	19	10	12
Ductility at 25° C., 5 centimeters per minute, centimeters	28	206	158	150	194	206	221	250+	250+	233	136	198

A sample of approximately 25 grams was immersed in distilled water at 70° F. immediately after mixing and, after a period of 24 hours immersion, was examined visually to determine the extent of stripping that had occurred.

A sample of approximately 35 grams was cured in air at 70° F. for 24 hours, then immersed in distilled water at 100° F. and, after a period of 24 hours immersion, was examined to determine the extent of stripping.

The results of the above tests are reported in accompanying tables as the estimated area that remained coated at the conclusion of the test.

The modified Nicholson test.—In this test a sample of approximately 100 grams of the mixture was cured in an oven at 140° F. for 24 hours, after which approximately 50 grams was placed in a flask partially filled with distilled water at 77° F. The stoppered flask was placed in a frame which rotates in a water bath at 77° F. After 30 minutes of rotation, the temperature of the water bath was raised to 100° F. and the rotation continued for an additional 15 minutes.

The appearance of the mixture at the end of 45 minutes of rotation is reported in terms of the estimated area that remained coated at the conclusion of the test.

Immersion-compression test.—Tests were made on cylinders of graded mixtures as described in the preceding article in this magazine.

Some specimens were tested immediately after curing and duplicate specimens were tested after immersion in water at room temperature for 4 days. Additional specimens from some of the mixtures were tested after having been subjected to various periods of alternate wetting and drying.

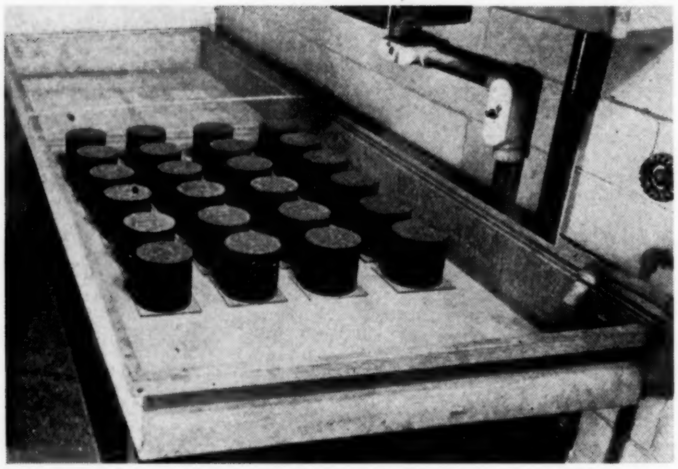
PREPARATION OF MIXTURES FOR COATING AND STRIPPING TESTS

Prior to preparing the mixtures, the aggregates were screened and the fraction passing the 3/8-inch sieve and retained on the No. 4 sieve was used. The dry weight of aggregate used for all mixtures was 600 grams. Aggregates used wet were placed in distilled water and allowed to soak for 24 hours prior to mixing. Before placing in the mixing bowl the wet aggregates were drained until they contained approximately 3.5 percent of free water, due allowance being made for absorption.

TABLE 4.—*Physical analyses of aggregates*

Type of aggregate	Description	Apparent specific gravity	Bulk specific gravity	Absorption	Los Angeles, percentage of wear
				Percent	Percent
Gravel No. 1	Gravel containing angular and subangular pieces of quartz, sandstone, quartzite, and chert.	2.64	2.53	1.7	42.8
Gravel No. 2	Gravel containing subangular pieces of quartz, quartzite, gneiss, granite, and schist.	2.69	2.63	.8	33.0
Granite No. 1	Crushed aplitic granite	2.67	2.61	.8	24.7
Granite No. 2	Crushed granite	2.76	2.72	.6	32.5
Quartzite	Crushed feldspathic quartzite.	2.63	2.60	.5	22.8
Limestone	Crushed argillaceous limestone.	2.75	2.72	.4	16.0
Limerock	Crushed limerock having a powdery surface.	2.58	2.37	3.4	41.3
Trap rock	Crushed trap rock (altered diabase).	2.95	2.86	1.1	------

APPARATUS USED IN PERFORMING THE MODIFIED NICHOLSON TEST FOR STRIPPING.



STORAGE TANK FOR SPECIMENS SUBJECTED TO ALTERNATE WETTING AND DRYING. THE TANK WAS FILLED AND DRAINED AS NECESSARY TO PRODUCE A WET OR DRY CONDITION.

Aggregates used wet or dry with liquid bituminous materials were at room temperature. The tar and liquid asphalts were heated to 120° and 175° F. respectively. In preparing the mixtures containing asphalt cement, both aggregate and bitumen were heated to 275° F. prior to mixing.

The amounts of additives used ranged from 0.5 to 4.0 percent of the weight of the bituminous material. This range included the particular percentages recommended by the individual producers.

The bitumen contents used were such that for all mixtures the film thickness on the aggregate particles was theoretically constant. The actual percentage of bitumen, including additives, ranged from 4.6 to 7.6 percent of the dry weight of the aggregate.

In the mixtures containing the additive that required quicklime, the proportion by weight was four parts of quicklime to one part of additive. In preparing the mixtures with wet aggregate, the lime was mixed with aggregate before applying the bituminous material. In preparing the dry mixes lime was applied 15 seconds after the bituminous material had been mixed with the aggregate. The additive was added to the bituminous material prior to the mixing operation.

A kitchen-type mixer was used in preparing the mixtures. This mixer was equipped with a special paddle composed of flexible mixing blades to provide proper mixing with the minimum of crushing. The operating speed was approximately 60 revolutions per minute and the mixing operation was continued until no further increase in coating was obtained or until a tendency to strip was observed.

At the completion of each mixing operation the following samples were taken:

(1) Approximately 25 grams for the immediate static immersion stripping test at 77° F.

(2) Approximately 35 grams for 24 hours of air curing at 70° F. to be followed by the static immersion stripping test at 100° F.

(3) Approximately 100 grams for 24 hours of oven curing at 140° F. to be followed by the modified Nicholson stripping test.

ALL ADDITIVES PRODUCED IMPROVEMENT IN COATING OF WET AGGREGATES

All the bituminous materials, both with and without additives, readily coated the aggregates used in this investigation when the aggregates were dry.

When the aggregates were wetted prior to mixing with the bituminous materials and in the manner

TABLE 5.—*Results of coating tests using wet aggregates. Estimated percentage of the area well coated*

Type of aggregate	Untreated material	Identification and percentage of additive in the bituminous material															
		A			B			C			D			E		F	G
		1	2	4	1	2	4	0.5	1	2	0.5	1	2	2	4	2	0.65
MIXTURES WITH MC-2 MATERIAL																	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Gravel No. 1	50	100	100	100	80	100	100	100	100	100	100		100	50	75	100	100
Gravel No. 2	50	100	100	100	80	95	100	100	100	100	100						100
Granite No. 1	65	95	95	100	60	80	95	90	100	100	95						100
Granite No. 2	65	95	100	100	90	100	100	100	100	100	95		100	70	95	100	100
Quartzite	40	90	95	100	50	100	100	100	100	100	95	100	100	40	85	100	100
Limestone	80	100	100	100	95	100	100	95	95	100	100	100	100				100
Limerock	50					100	100						100	90	100	100	
Trap rock	80				85												95
Average	60	97	98	100	77	96	99	98	99	100	98	100	100	63	89	100	99
MIXTURES WITH RT-5 MATERIAL																	
Gravel No. 1	90	100	100	100	80	80	85	95	95	100							100
Gravel No. 2	95	100	100	100	85	85	90	95	95	100							100
Granite No. 1	95	100	100	100	85	95	95	95	95	100	95						100
Granite No. 2	95	100	100	100	90	90	85	100	100	100							100
Quartzite	80	100	100	100	65	65	85	85	85	85	100						100
Limestone	95	100	100	100	85	85	95	60	60	[1] 70	95						100
Average	92	100	100	100	82	83	89	88	88	93	97						100
MIXTURES WITH RC-2 MATERIAL																	
Gravel No. 1	40				85	95		100	100				100	30	50	100	100
Granite No. 1	40				85	90		100	100		95						100
Quartzite	20				90	100		100	100		95		100	20	50	100	100
Limestone	50				95	100		90	100		95						100
Limerock	10					90	100						100	50	95	100	
Average	32				89	95	100	98	100		95		100	33	65	100	100

[1] In a test in which the bituminous material contained 4 percent of the additive, the estimated area well coated was 95 percent.

previously described, the coating obtained varied with the amount and kind of additives used. The results are shown in table 5 and are reported as the areas that upon visual inspection appeared to be well coated. Areas that appeared to be only slightly colored by the bituminous material were considered as uncoated. It will be observed that without an additive, the coating obtained with MC–2 asphalt varied from 40 to 80 percent and averaged 60 percent. With RC–2 asphalt the coating varied from 10 to 50 percent and averaged 32 percent, while with RT–5 tar it ranged from 80 to 95 and averaged 92 percent.

When additives were used with MC–2 and RC–2 asphalt a definite improvement in coating was always

TABLE 6.—*Results of static immersion tests at 70° F. on uncured mixtures using wet aggregates. Estimated percentage of area remaining coated*

MIXTURES WITH MC-2 MATERIAL

Type of aggregate	Untreated material	Identification and percentage of additive in the bituminous material															
		A			B			C			D			E		F	G
		1	2	4	1	2	4	0.5	1	2	0.5	1	2	2	4	2	0.65
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Gravel No. 1	0	10	20	80	30	60	95	90	95+	100	50		100	0	25	100	85
Gravel No. 2	0	15	70	90	40	95	95+	95	95+	100	85						90
Granite No. 1	0	10	15	40	10	30	80	30	70	95	40						50
Granite No. 2	0	15	70	90	20	80	95	100	100	100	90		100	5	25	100	95
Quartzite	0	20	70	85	20	70	90	60	100	100	15	100	100	0	15	100	80
Limestone	5	85	80	95	50	80	90	10	20	[1] 50	50	100	100				80
Limerock	0					90	95						[2] 95	20	70	[1] 50	
Trap rock	0				5												5

MIXTURES WITH RT-5 MATERIAL

Type of aggregate	Untreated material	A 1	A 2	A 4	B 1	B 2	B 4	C 0.5	C 1	C 2	D 0.5	D 1	D 2	E 2	E 4	F 2	G 0.65
Gravel No. 1	10	50	75	95	20	40	80	70	85	95							95
Gravel No. 2	10	75	80	95+	30	80	90	85	95	95+							95
Granite No. 1	0	15	50	70	20	50	95	80	90	95+	85						95+
Granite No. 2	10	70	60	85	75	85	90	90	95	95							95+
Quartzite	10	70	85	90	20	75	85	70	80	90	95+						100
Limestone	0	70	85	80	15	20	70	5	10	[3] 15	80						90

MIXTURES WITH RC-2 MATERIAL

Type of aggregate	Untreated material	A 1	A 2	A 4	B 1	B 2	B 4	C 0.5	C 1	C 2	D 0.5	D 1	D 2	E 2	E 4	F 2	G 0.65
Gravel No. 1	5				75	95		95	95				100	0	5	100	95
Granite No. 1	5				20	35		80	85		85						90
Quartzite	0				40	85		90	90		90		95+	5	15	95+	95
Limestone	5				60	85		50	75		80						95
Limerock	0					85	95+						[1] 80	20	75	[2] 80	

[1] In a test in which the bituminous material contained 4 percent of the additive, the estimated area remaining coated was 95 percent.
[2] In a test in which the bituminous material contained 4 percent of the additive, the estimated area remaining coated was 100 percent.
[3] In a test in which the bituminous material contained 4 percent of the additive, the estimated area remaining coated was 75 percent.

TABLE 7.—*Results of static immersion tests at 100° F. on air-cured mixtures using wet aggregates. Estimated percentage of area remaining coated*

MIXTURES WITH MC-2 MATERIAL

Type of aggregate	Untreated material	Identification and percentage of additive in the bituminous material															
		A			B			C			D			E		F	G
		1	2	4	1	2	4	0.5	1	2	0.5	1	2	2	4	2	0.65
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Gravel No. 1	10	5	15	85	95	100	100	95+	95	100	60		100	70	85	100	100
Gravel No. 2	20	15	85	100	95+	100	100	100	100	100	100						100
Granite No. 1	5	5	10	95	75	95+	100	100	100	100	85						95+
Granite No. 2	10	10	30	100	95+	100	100	100	100	100	85		100	20	75	100	100
Quartzite	5	5	15	100	90	100	100	85	100	100	10	80	100	10	80	100	90
Limestone	10	95	95+	100	95	95+	100	90	90	95+	95	100	100				95+
Limerock	20					100	100						100	95	100	95+	
Trap rock	5				50												80

MIXTURES WITH RT-5 MATERIAL

Type of aggregate	Untreated material	A 1	A 2	A 4	B 1	B 2	B 4	C 0.5	C 1	C 2	D 0.5	D 1	D 2	E 2	E 4	F 2	G 0.65
Gravel No. 1	100	100	100	100	95	95	95	95+	100	100							100
Gravel No. 2	95	100	95+	100	90	95+	100	100	100	100							100
Granite No. 1	95	100	95	100	95	100	100	100	100	100	100						100
Granite No. 2	100	100	100	100	95+	95+	100	100	100	100							100
Quartzite	100	95+	100	100	95	95+	100	95+	100	100	100						100
Limestone	30	100	100	100	80	95	100	40	50	70	95+						100

MIXTURES WITH RC-2 MATERIAL

Type of aggregate	Untreated material	A 1	A 2	A 4	B 1	B 2	B 4	C 0.5	C 1	C 2	D 0.5	D 1	D 2	E 2	E 4	F 2	G 0.65
Gravel No. 1	10				90	95+		95+	100				100	40	65	100	100
Granite No. 1	5				70	95		100	100		95+						95+
Quartzite	10				90	95		100	100		90		100	10	40	100	100
Limestone	40				90	95+		95	95		95						95+
Limerock	40					90	100						95+	80	95	95+	

Mixtures For The Coating And Stripping Tests Were Prepared in a Kitchen-Type Mixer.

obtained with some percentage of additive but the optimum percentage of a given additive was not the same for all aggregates.

When the additives were used with tar, the benefit obtained was less apparent as the untreated tar coated the aggregate reasonably well. Of the five additives used with the tar, 100 percent coating of all aggregates was obtained with 1 percent of additive A and with 0.65 percent of additive G. Approximately the same result was obtained with 0.5 percent of additive D on the three aggregates used with tar. No improvement was afforded by the use of as much as 4 percent of additive B with tar. Use of additive C with tar resulted in complete coating of four of six aggregates with 2 percent of additive. With one aggregate practically the same result was obtained with 0.5, 1, and 2 percent of additive C as with the tar alone. With the remaining aggregate, the tar alone was more satisfactory than when 2 percent of additive C was used, and 4 percent of this additive produced no improvement over the tar without additive.

RESULTS OF STRIPPING TEST, ON MIXTURES MADE WITH WET AGGREGATE DISCUSSED

The effect of the additives in improving the ability of the three liquid bituminous materials to adhere to wet aggregate after being subjected to the action of water in the static immersion test is shown in tables 6 and 7.

Table 6 gives the results of the static immersion test on the wet, uncured mixtures. The conditions under which this test is made are admittedly severe as is evidenced by the fact that at its conclusion a maximum of 10 percent of area remained coated when additives were not used. However, when additives were used the coating retained was substantially increased although, in the case of additive E, this increase was substantial with one aggregate only.

The improvement obtained with additives varied considerably. It varied with the kind and percentage of additive, with the type of bituminous material, and with the type of aggregate. In practically every instance, increasing the amount of additive resulted in increased resistance to stripping but the rate of improvement varied considerably for different additives. Also, the different additives varied considerably in their effectiveness with different aggregates.

Table 7 gives the results of the static immersion test made at 100° F. on the mixtures that contained wet aggregate and which were air-cured at 70° F. for 24 hours before testing. It will be observed that when additives were not used, the asphaltic materials did not provide a coating resistant to stripping but that the tar did except when used with limestone.

In general, when additives were used, definite improvement was obtained, although the improvement in the tar mixtures was limited to the limestone since the other tar-coated aggregates showed good resistance to stripping without an additive. The amount of improvement resulting from the use of the additives, as measured by this test, varied as in the tests of the uncured mixtures.

The tests with the untreated materials showed that the resistance to stripping had been greatly improved by the curing prior to the test and it appears that the benefits obtained by curing, in general, more than compensate for the detrimental effect of the higher test temperatures. An exception was found when 2 percent or less of additive A was used with MC–2 asphalt. With such materials some aggregates gave more satisfactory results when the mixtures were tested immediately after mixing.

RESULTS OF STRIPPING TESTS ON MIXTURES MADE WITH DRY AGGREGATES

Tables 8, 9, and 10 give the results obtained on the mixtures prepared with dry aggregates. Tables 8 and 9 show the results of the static immersion tests on the uncured and on the air-cured samples, respectively, and table 10 gives the results of the modified Nicholson tests.

Table 8 shows that when mixtures containing no additives were tested without curing, the amount of coating retained varied considerably, not only with the aggregate used but also with the kind of bituminous material. With MC–2 asphalt, the maximum coating retained was 50 percent; with RC–2 asphalt, the maximum was 85 percent; with tar, an excellent coating was retained on all aggregates except the limestone. It is interesting to note that in the untreated MC–2 and RC–2 mixtures, this aggregate showed a better resistance to stripping than any of the others, while in the tar mixtures it showed the poorest resistance of any of the aggregates. The actual amount of coating retained was greater with RC–2 asphalt than with tar.

When additives were used, considerable improvement resulted in most cases. Practically, complete coating was retained with all percentages of additives B, C,

TABLE 8.—*Results of static immersion tests at 70° F. on uncured mixtures using dry aggregates. Estimated percentage of area remaining coated*

Aggregate	Untreated material	Identification and percentage of additive in the bituminous material: A			B		C		D	G
		1	2	4	1	2	0.5	1	0.5	0.65
MIXTURES WITH MC-2 MATERIAL										
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Gravel No. 1	25	20	70	90	100	100	95	95+	95	100
Gravel No. 2	50	60	90	95+	100	100	100	100	100	100
Granite No. 1	30	30	40	70	100	100	100	100	100	100
Granite No. 2	10	20	15	50	100	100	100	100	90	100
Quartzite	15	30	60	75	95	100	95+	100	90	95+
Limestone	50	95	95	100	100	100	95+	100	100	100
Trap rock	10	----	----	----	100	----	----	----	----	100
MIXTURES WITH RT-5 MATERIAL										
Gravel No. 1	100	95	90	95+	100	95+	100	100	----	100
Gravel No. 2	100	100	100	100	100	100	100	100	----	100
Granite No. 1	100	85	80	85	100	100	100	100	100	100
Granite No. 2	95+	50	30	20	100	100	100	100	----	100
Quartzite	100	95	85	75	90	100	95+	100	100	100
Limestone	70	100	100	100	90	95+	70	80	100	100
MIXTURES WITH RC-2 MATERIAL										
Gravel No. 1	75	----	----	----	100	100	100	95+	----	95+
Granite No. 1	25	----	----	----	100	100	100	100	100	95+
Quartzite	60	----	----	----	95	100	95	95+	95+	95+
Limestone	85	----	----	----	95+	100	95	100	100	95+

TABLE 9.—*Results of static immersion tests at 100° F. on air-cured mixtures using dry aggregates. Estimated percentage of area remaining coated*

Aggregate	Untreated material	Identification and percentage of additive in the bituminous material: A			B		C		D	G
		1	2	4	1	2	0.5	1	0.5	0.65
MIXTURES WITH MC-2 MATERIAL										
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Gravel No. 1	25	20	90	95+	100	100	80	95	95+	100
Gravel No. 2	30	95	100	100	100	100	100	100	100	100
Granite No. 1	15	40	95	95	95+	100	100	100	95+	95+
Granite No. 2	10	30	65	75	100	100	100	100	95	100
Quartzite	15	20	90	80	95+	100	85	100	50	90
Limestone	30	95	100	100	100	100	90	100	95+	95+
Trap rock	15	----	----	----	100	----	----	----	----	100
MIXTURES WITH RT-5 MATERIAL										
Gravel No. 1	100	100	95+	100	100	100	100	100	----	100
Gravel No. 2	100	100	100	100	100	100	100	100	----	100
Granite No. 1	100	95	100	95	100	100	100	100	100	100
Granite No. 2	100	50	70	30	100	100	100	100	----	100
Quartzite	100	95	95	90	100	100	100	100	95+	100
Limestone	75	100	100	100	95	100	80	80	95+	95+
MIXTURES WITH RC-2 MATERIAL										
Gravel No. 1	85	----	----	----	100	100	100	100	----	100
Granite No. 1	50	----	----	----	100	100	100	100	100	100
Quartzite	40	----	----	----	100	100	100	100	100	100
Limestone	90	----	----	----	100	100	95+	95+	100	100

D, and G, except that tar with additive C showed only slight improvement over tar alone when used with limestone.

Additive A was not used with RC-2 asphalt. When used with MC-2 asphalt, some improvement resulted, which generally increased with the amount of additive, but results varied considerably with different aggregates. When additive A was used with tar, no improvement resulted except in the case of the limestone. When the gravels were used, the results with and without additive A in tar were substantially the same. With the granites and quartzite, the untreated tar was more satisfactory than the tar containing additive A and it will be noted that with two of these aggregates, that is, with granite and quartzite, greater amounts of additive A in tar were less satisfactory than small amounts.

The results of the tests of mixtures containing dry aggregates which were air-cured before testing are given in table 9. In the tests without additives the

TABLE 10.—*Results of modified Nicholson stripping tests on oven-cured mixtures using dry aggregates. Estimated percentage of area remaining coated at the end of the 100° F. test period*

Aggregate	Untreated material	Identification and percentage of additive in the bituminous material								
		A			B		C		D	G
		1	2	4	1	2	0.5	1	0.5	0.65
MIXTURES WITH MC-2 MATERIAL										
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Gravel No. 1	90	95	90	100	95	100	95	100	95	90
Gravel No. 2	90	100	100	100	85	100	100	100	95	100
Granite No. 1	60	95	95	95	95	100	100	100	95+	100
Granite No. 2	80	95	100	100	100	100	100	100	100	100
Quartzite	75	95	90	90	100	100	100	95	100	100
Limestone	100	100	100	100	100	100	100	95+	100	100
Trap rock	80				95					100
MIXTURES WITH RT-5 MATERIAL										
Gravel No. 1	100	100	100	100	95	90	100	100		100
Gravel No. 2	100	100	100	100	95	100	100	100		100
Granite No. 1	95	100	100	100	100	100	100	100		100
Granite No. 2	100	100	100	95	100	100	100	100		100
Quartzite	100	100	100	100	95	100	100	100		100
Limestone	100	100	100	100	100	100	95	100		100
MIXTURES WITH RC-2 MATERIAL										
Gravel No. 1	90				100	95	95	100		100
Granite No. 1	85				95	100	100	100		100
Quartzite	95				95	95	90	100		100
Limestone	100				100	100	100	100		100

results were similar to those shown in table 8 in that the coating retained varied considerably. They were least satisfactory with MC–2 asphalt, more satisfactory with RC–2 asphalt, and complete coating with tar was retained except on the limestone

When additives were used, the results were also similar to those with the uncured mixtures shown in table 8 in that practically complete coating was retained with all percentages of additives B, C, D, and G, and that additive C was only slightly beneficial when used in tar-limestone mixes. Additive A was beneficial with MC–2 asphalt in varying degrees. It was beneficial with tar only when used with limestone. With granite No. 2 and tar it was less satisfactory than tar alone and the results obtained were still less satisfactory when the amount of additive A was increased from 2 to 4 percent.

The results of the tests made by the modified Nicholson method on oven-cured mixtures using dry aggregates are given in table 10. From these results it will be observed that with several aggregates some improvement resulted from using additives with MC–2 asphalt. However, the conditions of the test were not sufficiently severe to demonstrate differences between the additives or the effect of using different percentages of additive. The effect of agitation at the testing temperature of 100° F. was apparently more than compensated for by the 24 hours of oven curing at 140° F.

This study was confined mainly to the use of liquid materials in order to compare results obtained when unheated aggregates, wet or dry, were used. However, since the opinion has been frequently expressed that a coating of asphalt cement on aggregate is generally resistant to moisture, a limited number of tests with asphalt cement were included in this investigation in order to obtain comparative data on the subject.

An asphalt cement of 120–150 penetration, with and without additives B and C, was used to coat gravel No. 1, granite No. 1, quartzite, and limestone. In preparing these mixtures the aggregates were heated to 275° F. All aggregates coated readily whether or not additives were used.

These mixtures were subjected to the three stripping tests. At least 90 percent of the coating was retained in every instance and in 16 of 24 tests 100 percent was retained. For all practical purposes it can be stated that the asphalt cement effectively coated the four aggregates used and the coating was not affected in the tests applied. The test data are not included in the tables and they do not warrant further discussion.

Considering the results of stripping tests in tables 6, 7, 8, 9, and 10, the following statements appear to be warranted:

1. In practically all cases, additives were of benefit in the retention of liquid asphaltic films on aggregate subjected to the action of water.
2. The benefit thus obtained is increased if the coated aggregate is allowed to cure before being subjected to moisture.
3. Additives appear to be of little benefit when used with tar except when mixtures of tar and wet aggregate are subjected to the action of water before curing.
4. The effectiveness of additives varies both with the bituminous material and with the aggregate used with them.
5. The optimum percentage of a given additive is not the same for all aggregates.

ADDITIVES IMPROVE STABILITY OF DENSE-GRADED MIXTURES SUBJECTED TO MOISTURE

To obtain information on the effect of additives in reducing the loss of compressive strength of dense-graded bituminous mixtures due to absorbed moisture, a number of specimens were made and subjected to the immersion-compression test. These specimens were cylinders 4 by 4 inches except those containing trap rock. These were 3 by 3 inches. The composition of the bituminous mixtures used in all of the specimens was as follows:

TABLE 11.—*Results of immersion-compression test. Each value is the average of values from 3 specimens MC–2 asphalt used in all mixes*

Aggregate and additive used	Bitumen-aggregate ratio by weight		Volumetric analysis of cured specimens			Compressive-strength tests on dry specimens	Tests on specimens immersed in water 4 days			Retained strength [2]
	As mixed	After curing	Aggregate	Bitumen	Air		Compressive strength	Absorption [1]	Volumetric swell	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*
GRANITE No. 1, ROUND 1:										
None	6.0	5.6	81.3	12.3	6.4	62	17	3.8	4.6	27
2 percent A	6.0	5.6	82.0	12.5	5.5	61	55	1.4	.4	90
1 percent B	6.0	5.6	82.0	12.5	5.5	59	57	1.5	.6	97
0.5 percent D	6.0	5.6	81.8	12.4	5.8	62	43	1.9	1.4	69
0.65 percent G	6.0	5.6	82.3	12.6	5.1	65	53	1.6	1.1	82
GRANITE No. 1, ROUND 2:										
None	6.0	5.6	81.8	12.3	5.9	58	10	3.7	5.8	17
2 percent A	6.0	5.6	82.3	12.5	5.2	58	54	1.1	.1	93
1 percent B	6.0	5.6	82.4	12.5	5.1	55	54	1.0	.5	98
0.5 percent D	6.0	5.6	82.3	12.5	5.2	52	34	1.7	1.8	65
0.65 percent G	6.0	5.6	82.4	12.4	5.2	58	43	1.6	1.2	74
GRANITE No. 1, ROUND 3:										
None	6.0	5.6	81.6	12.3	6.1	44	6	5.1	8.0	14
2 percent A	6.0	5.6	81.5	12.3	6.2	45	36	1.6	.3	80
1 percent B	6.0	5.6	81.8	12.3	5.9	44	43	1.6	.5	98
0.65 percent G	6.0	5.6	81.6	12.4	6.0	45	27	2.6	2.6	60
LIMESTONE:										
None	6.0	5.6	83.3	12.9	3.8	56	39	1.6	1.7	70
2 percent A	6.0	5.6	83.8	13.0	3.2	49	51	.6	0	104
1 percent B	6.0	5.6	83.6	13.0	3.4	50	56	.8	.3	112
0.5 percent D	6.0	5.6	83.5	12.9	3.6	49	53	.8	.1	108
0.65 percent G	6.0	5.6	83.8	13.0	3.2	51	60	.6	.1	118
GRAVEL No. 1:										
None	6.0	5.6	81.8	12.3	5.9	43	33	1.6	.4	77
2 percent A	6.0	5.6	81.8	12.4	5.8	45	36	1.4	0	80
1 percent B	6.0	5.6	81.9	12.3	5.8	39	39	1.2	0	100
1 percent D	6.0	5.6	81.9	12.3	5.8	38	36	1.5	.3	95
GRANITE No. 2:										
None	5.7	5.3	83.1	12.2	4.7	64	35	1.5	1.3	55
2 percent A	5.7	5.3	83.0	12.3	4.7	61	50	1.0	.1	82
1 percent B	5.7	5.3	83.2	12.2	4.6	61	59	1.0	.1	97
1 percent D	5.7	5.3	83.0	12.3	4.7	61	57	1.2	.5	93
TRAP ROCK:										
None	5.5	5.1	81.2	11.7	7.1	57	0	----	----	0
1 percent B	5.5	5.1	81.5	11.7	6.8	60	62	1.5	.3	103
0.65 percent G	5.5	5.1	81.1	11.7	7.2	65	45	2.1	1.0	69

[1] Ratio of moisture to aggregate by weight.
[2] Ratio of compressive strength of the immersed specimens to the compressive strength of the corresponding dry specimens.

Coarse aggregate.—Five of the materials used in the coating and stripping tests graded from 0.5 inch to No. 10.

Fine aggregate.—Potomac River sand passing the No. 10 sieve.

Dust.—Silica dust.

Bitumen.—MC–2 cut-back asphalt without additive and with the minimum amount of additive shown to have been reasonably satisfactory in the stripping test.

The composition, by weight, was as follows:

Aggregate sizes:	*Percent*
0.5 inch to No. 4	47
No. 4 to No. 10	13
No. 10 to No. 200	30
Passing No. 200	10

The bitumen content, in terms of dry aggregate, was 5½ to 6 percent.

The mixtures were prepared in a laboratory twin-pug mixer. Aggregates were dry and at room temperature. Bituminous materials were heated to 175° F. The period of mixing was 1½ minutes and was sufficient to insure uniform coating.

When the mixing operation was completed, the mixture was placed in a large pan and air cured at room temperature for 24 hours before molding. During this period it was stirred occasionally to expedite curing.

The test specimens were molded by direct compression, using the double plunger method, and a load of 3,000 pounds per square inch was maintained for 2 minutes. They were cured in an oven at 140° F. for 24 hours and then allowed to cool overnight to room temperature.

Immediately thereafter one-half of the specimens were tested for compressive strength and the others were immersed in water at approximately 77° F. for 4 days and then, while still wet, were also tested for compressive strength.

To provide information on the permanency of any benefit obtained by the use of additives, an additional series of test specimens was made. The coarse aggregates used were gravel No. 1 and granite No. 2. The fine aggregate, filler, and bitumen were the same as those used in the specimens previously described.

Because of the number of specimens required in this series, a slight variation had to be made in their preparation. All the mixtures from which they were formed were made in one day but only one-third of them could be molded or oven cured at one time. A third of the total required was therefore molded on each of three successive days, oven cured for 24 hours immediately after molding, and then stored in air until the entire series had been thus processed. Consequently, the average curing time before molding, as well as the period of air storage after oven curing, was two days instead of one. A test group included specimens representing each of these curing and storage conditions.

Some of the specimens of this series were tested as previously described, that is, some were tested after oven curing and some were immersed in water for 4 days before being tested.

Other specimens of this series were subjected to several cycles of immersion in water and subsequent air curing before being tested. A cycle consisted of

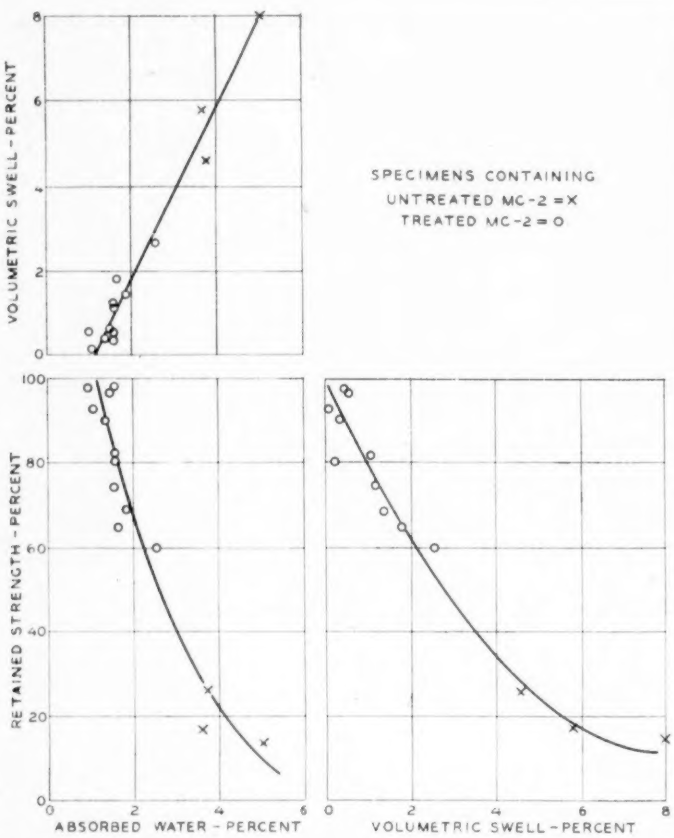


FIGURE 1.—RELATIONS BETWEEN ABSORBED WATER, VOLUMETRIC SWELL, AND RETAINED STRENGTH AFTER 4 DAYS IN WATER; GRANITE NO. 1 MIXTURES.

immersion in water at approximately 77° F. for 4 days, followed by drying in laboratory air for 10 days. Specimens subjected to this method of aging were tested at the end of the immersion period while they were still wet. Duplicate specimens, cured in air, were also tested dry after the same storage period used for the wet specimens. In addition, a number of specimens were buried in soil out of doors with the upper face exposed to the elements. Testing of these specimens will be delayed until they have aged considerably.

The compressive-strength test to which all specimens were subjected was made on the unconfined specimen at a temperature of 77° F. The load was applied to provide vertical deformation at the rate of 0.05 inch per minute per inch of height of specimen. The compressive strength was taken as the maximum unit load recorded.

The results of this test are given in table 11 and show that, in every instance when additives were used, the amount of moisture absorbed was definitely reduced. They reduced absorption from 0.1 to 3.5 percent, the average being 1.6 percent. The volumetric swell resulting from the absorbed moisture was also decreased by the use of additives. The reduction ranged from 0.1 to 7.7 percent and averaged 3.1 percent. In general the swell was approximately proportional to the absorbed moisture.

The specimens not subjected to the action of water varied in compressive strength with different coarse aggregates as might be expected, but there was practically no difference in strength as a result of the use or nonuse of any of the additives.

When the specimens were immersed in water for 4 days, however, the effect of moisture on compressive strength was very pronounced. In every instance, when additives were not used, the compressive strength retained, in terms of the strength of dry specimens, was greatly reduced. It ranged from 0 to 77 percent and averaged 44 percent for the five aggregates used.

When additives were used, the percentage of strength retained in all cases was much greater than when they were not used. It ranged from 60 to 118 percent and averaged 90 percent. The effect of the different additives varied in degree but in every instance they were beneficial. It is interesting to note that the retention of compressive strength, due to the use of additives, expressed as a percentage is approximately equal to the corresponding reduction in percentage of absorbed moisture. As shown in table 12, this relation appears to hold despite the considerable range in density and absorption obtained with the different aggregates.

Figure 1 shows the relation between the absorption, volumetric swell, and retained strength for the treated and untreated mixes containing MC-2 asphalt and granite No. 1. Similar tests of other aggregates were insufficient in number to establish curves and they are therefore not included in this figure. However, it would be expected that these and other aggregates would produce curves of the same general types as those shown.

BENEFITS OBTAINED BY USING ADDITIVES SEEM TO HAVE A CONSIDERABLE DEGREE OF PERMANENCE

The early advantages gained by the use of additives are definitely shown by the results obtained in the 4-day immersion tests. However, these results do not provide information on the long-time retention of such advantages and, to obtain such information, a number

TABLE 12.—*Comparison between absorption and retained strength values for specimens containing MC-2 asphalt after 4 days of immersion* [1]

Coarse aggregate	Water absorbed, average value		Retained strength, average value		Change due to additives		
	Untreated mix	Treated mixes	Untreated mix	Treated mixes	Difference in percentages of water absorbed	Reduction in absorption	Difference in percentages of strength retained
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Granite No. 1 (round 1)	3.8	1.60	27	85	2.20	58	58
Granite No. 1 (round 2)	3.7	1.35	17	83	2.35	64	66
Granite No. 1 (round 3)	5.1	1.93	14	79	3.17	62	65
Limestone	1.6	0.70	70	111	.90	56	41
Gravel No. 1	1.6	1.37	77	92	.23	14	15
Granite No. 2	1.5	1.07	55	91	.43	29	36

[1] Values taken from table 11.

of specimens identical with those used in the immersion-compression test were prepared with gravel No. 1 and granite No. 2. Some of these specimens were stored in air for 74 days before testing and others were alternately wetted and dried for the same period before testing. The results of these tests are given in table 13 together with the corresponding test results obtained in the 4-day immersion-compression test. Test results are arranged in four groups, each representing a different storage condition. Groups 1 and 2 represent the storage conditions used in the immersion-compression test and the results given were taken from table 11.

The specimens in group 3 were tested wet after having been alternately wetted and dried for a 74-day period. This storage period began and also ended with a wetting period. The specimens were immersed in water six times and permitted to air dry after each of the first five immersions. The period for each immersion was 4 days and that for each air drying was 10 days. Thus, out of the 74-day storage period, the specimens were in water for a total time of 24 days and in air for a total of 50 days.

The specimens of group 4 were stored for 74 days in laboratory air and then tested dry.

A comparison of the results of group 3 with those of group 2 show that the final water contents for the specimens which were subjected to the 74 days of alternate wetting and drying were higher than those for the specimens which were stored in water for only 4 days. Likewise, the volumetric swells were higher. But increases in absorption and swell due to the five extra immersions did not result in decreased values for compressive strengths. On the contrary, the increases range from 6 to 42 pounds per square inch. Apparently, most of the increase is due to the air curing which occurred during the 50 days of dry storage. This is rather definitely indicated by comparing the results of group 4 with those of group 1 and noting the increased strength which resulted from 74 days of air storage.

Reference to the 4-day strength values shows that all three additives were effective in increasing the compressive strength. The amount of the increase varied with the aggregate and with the additive. The least increase in compressive strength was produced by additives A and D when used with the gravel No. 1, and the greatest amount occurred with additive B in the mix containing the granite No. 2.

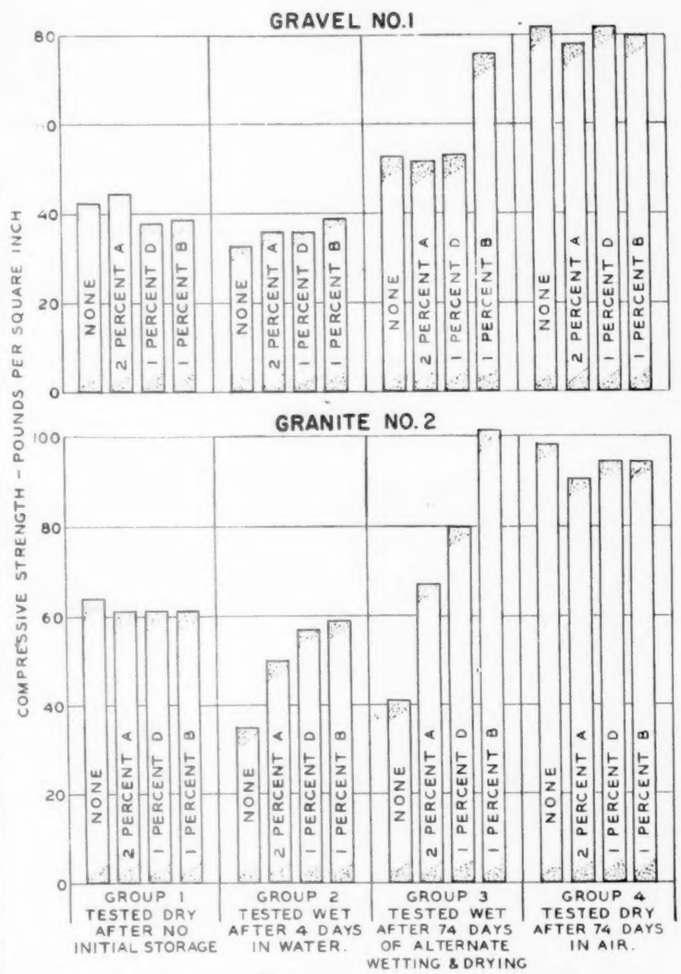


FIGURE 2.—EFFECT OF ADDITIVES IN IMPROVING THE RETENTION OF STABILITY MIXTURES CONTAINING MC–2 ASPHALT.

The compressive strengths given in table 13 are shown graphically in figure 2. Group 2 of this figure illustrates the relative effect of the three additives in providing higher compressive strengths after the initial 4-day immersion in water. Additives A and D were the least effective and additive B was the most effective. The additives were much more effective when used with granite No. 2 than when used with gravel No. 1.

TABLE 13.—*Comparison of results obtained on specimens subjected to 4 different storage conditions. Each value is the average of values obtained from 3 specimens*

Kind of aggregate and additive in MC–2 material	Compressive strength				Water content [1]			Volumetric swell	
	Group 1, no initial storage, tested dry	Group 2, 4 days in water, tested wet	Group 3, 74 days alternate wetting and drying, tested wet	Group 4, 74 days in air, tested dry	Group 2, after 4 days in water	Group 3, 74 days alternate wetting and drying: Prior to final 4 days in water	Group 3, 74 days alternate wetting and drying: After final 4 days in water	Group 2, after 4 days in water	Group 3, after 74 days alternate wetting and drying
	Lb. per sq. in.	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
GRAVEL NO. 1:									
None	43	33	53	82	1.6	0.6	2.0	0.4	0.7
2 percent A	45	36	52	78	1.4	.7	1.7	0	.3
1 percent D	38	36	53	82	1.5	.7	2.3	.3	1.2
1 percent B	39	39	76	80	1.2	.8	1.7	0	.1
GRANITE NO. 2:									
None	64	35	41	98	1.5	.3	2.5	1.3	2.9
2 percent A	61	50	67	91	1.0	.5	1.3	.1	.3
1 percent D	61	57	80	95	1.2	.4	1.6	.5	1.3
1 percent B	61	59	101	95	1.0	.5	1.3	.1	.3

[1] Ratio of moisture to aggregate by weight.

Group 3 shows the effect of the additives in improving the ability of specimens to retain compressive strength after having been subjected to a 74-day period of alternate immersion in water and air drying. Here, as in group 2, the additives were much more effective when used in the mixes containing granite No. 2. As in group 2, additive B was more effective than the other two additives. The effectiveness of additive B is emphasized further by the fact that, when used with granite No. 2, it produced a higher compressive strength after a 74-day period of wetting and drying than it did after the same period of straight air curing.

In the granite No. 2 mixes, additive D was more effective than additive A but, in the gravel No. 1 mixes, neither was highly effective since both additives failed to produce compressive strengths much greater than those obtained without additive.

CONCLUSIONS

In summarizing the results of this investigation the following statements appear to be warranted:

1. Additives are available that facilitate the coating of wet aggregate with liquid bituminous materials.
2. Additives are available that greatly increase the resistance of bituminous films to stripping in the presence of moisture.
3. The use of additives with tar does not appear to be warranted except possibly when mixing must be done under particularly adverse conditions, such as during a rain or immediately prior thereto.
4. Additives appear to have no detrimental effect upon the bituminous material with which they are used.
5. Additives appear to have no material effect on the original compressive strength of bituminous mixtures.
6. Additives are available that will reduce the loss of stability of bituminous mixtures due to the detrimental action of water.
7. The benefits afforded by additives appear to have considerable permanence but the degree of permanence was not disclosed by these tests.
8. The immersion-compression test provides a useful measure of the benefits to be derived from the use of additives.

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